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SCIENCE ON THE MARCH

UNIT NINE

MAGNETS AND ELECTRIC POWER

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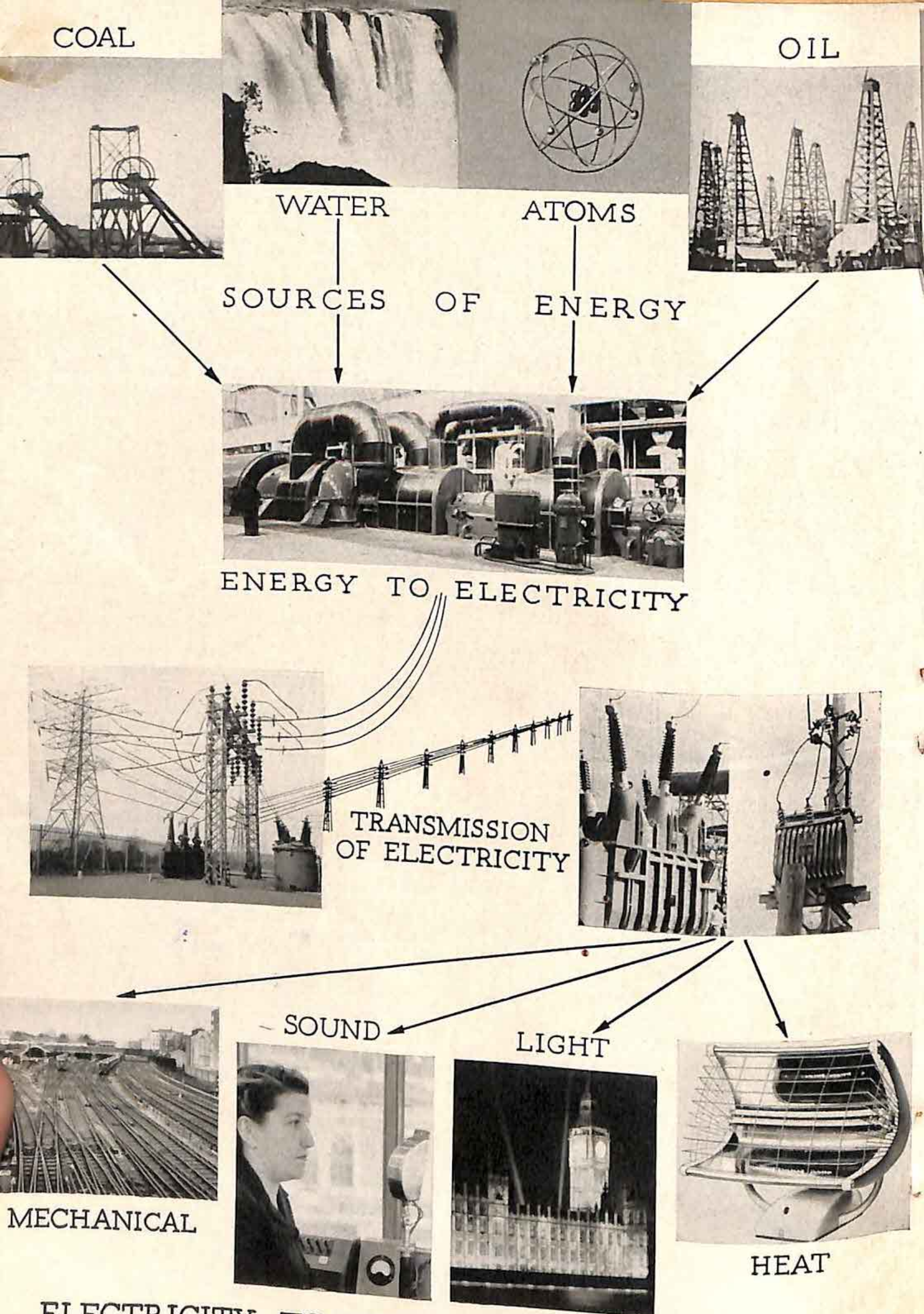

SOURCES OF ENERGY

ENERGY TO ELECTRICITY

TRANSMISSION OF ELECTRICITY

ELECTRICITY TO DIFFERENT FORMS OF ENERGY

SCIENCE ON THE MARCH

UNIT NINE

MAGNETS AND ELECTRIC POWER

Philip E. Heafford

General Editor: **Charles H. Dobinson**

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First published in Great Britain 1957
Third impression 1960

This unit has been especially written for SCIENCE ON THE MARCH by Philip E. Heafford, M.A., B.Sc., Lecturer in the University of Oxford Department of Education. The general editor of the units is Charles H. Dobinson, M.A., B.Sc., Professor of Education in the University of Reading.

Every photograph in this unit, unless otherwise acknowledged, was taken by Philip E. Heafford

The first twelve units of SCIENCE ON THE MARCH:

1. The Air and You.
2. Water and Life.
3. The Weather and the Earth.
4. Life and Food.
5. Health.
6. Energy and Engines.
7. Hearing and Seeing.
8. Electric Currents.
9. Magnets and Electric Power.
10. Earth and Universe.
11. Heating and Cooling.
12. Birth and Growth.

Made and Printed in Great Britain by Butler & Tanner Ltd, Frome and London

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For the frontispiece photographs we are indebted to the following: British Railways (Southern Region); Ferranti, Ltd.; Ewing Galloway; Central Electricity Authority; P. E. Heafford; National Coal Board; N. T. Peters; United States Information Service.

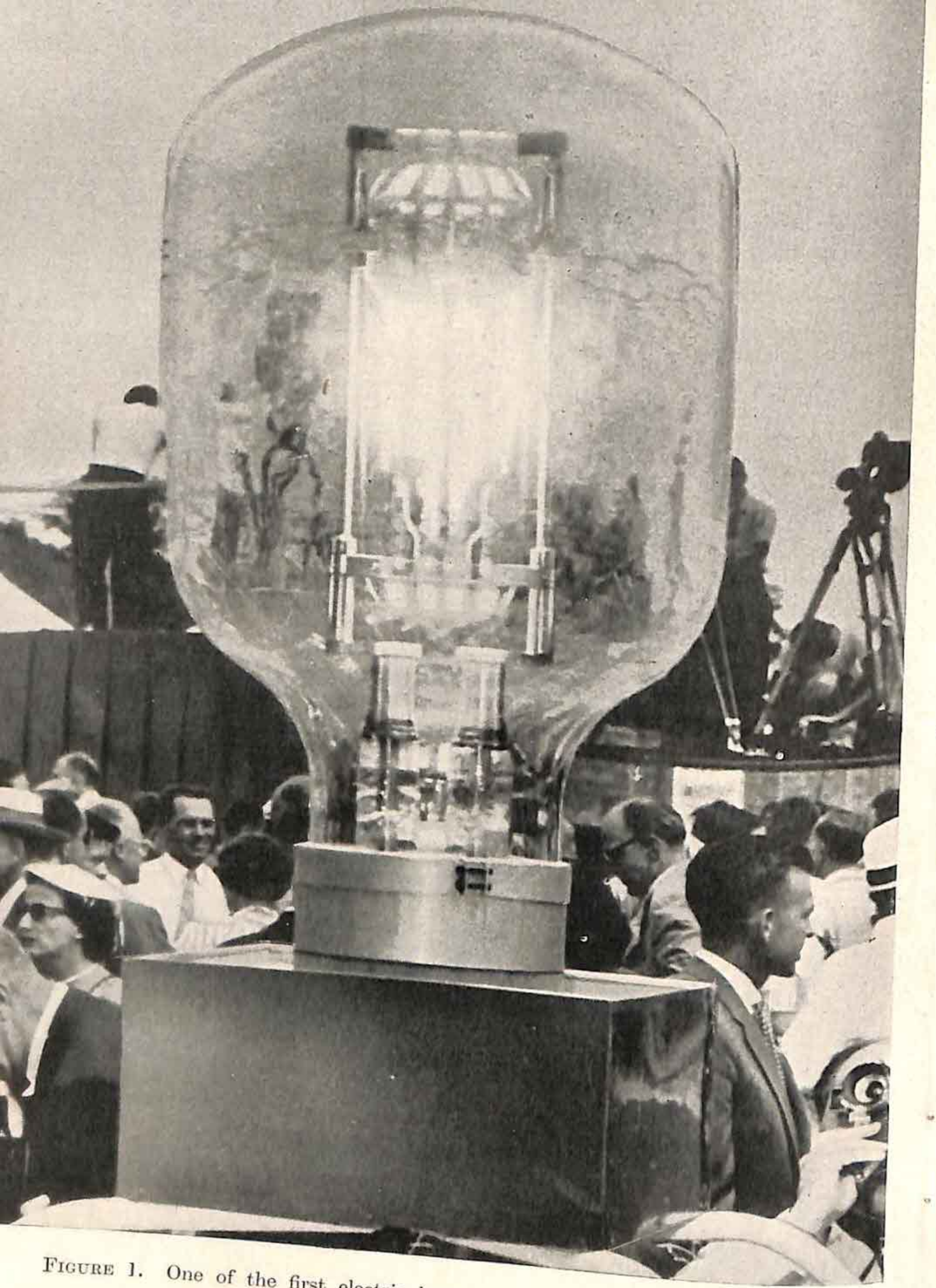


FIGURE 1. One of the first electric lamps to be lit by electricity generated from nuclear power.

Magnets and Electric Power

ELECTRICITY in the modern world is at work in the service of man and has done perhaps more than any other single thing to change our way of living in the last 100 years.

We marvel at the way the engineer builds his machines to the designs of the patient and careful scientist. There is nothing miraculous about the work of a scientist. The inventions of the electric motor and generator were not miracles. They were the result of hard work, of the thorough study of what was known about magnetism and electricity, and of careful experiments each made with a definite object in view.

A scientist plans his experiments to lead step by step from one idea to the next. In this Unit there will be examples of the way that carefully planned and simple experiments lead to better understanding. As you read, think why you perform these experiments, and how the results lead you to the next stage. Do not read about the second question until you understand clearly the answer to the first, and so on right through the book. In this way you will be making progress surely and steadily, in the same way as a true scientist.

In this Unit you will learn much about magnets and electric currents. Michael Faraday performed many experiments to find the relation between magnetism and electricity. Scientists have used his discoveries to build up the electrical industry of today.

You will learn also how electricity is generated on a large scale, how it is transmitted, and how it is used to help us with our lighting, heating, cooking, and transport.

Problem A: **WHAT IS MAGNETISM?**

A tale is told that long ago a shepherd sat down on a rock and rested his crook against it. When he got up he found to his surprise that the iron crook seemed to be stuck to the rock! The shepherd was sitting on loadstone, a dark brown iron ore that possesses the peculiar property of attracting iron. More than that, if suspended freely it will always come to rest in a certain fixed direction. It is believed that the first specimens of *loadstone* were found over 2000 years ago near Magnesia, an ancient city in Asia Minor. The Chinese, from very early times, used this stone to help them on their travels over land and sea. They would hang it up so that it could " lead " them and hence it got its name "loadstone", i.e. "leading stone". This stone is often called *magnetite*. The magnetic compass of today does the same thing. A steel magnet, made by man in various ways, has the same property as magnetite. The word *magnet*, as you can guess, is derived from the name of that ancient city of Magnesia.

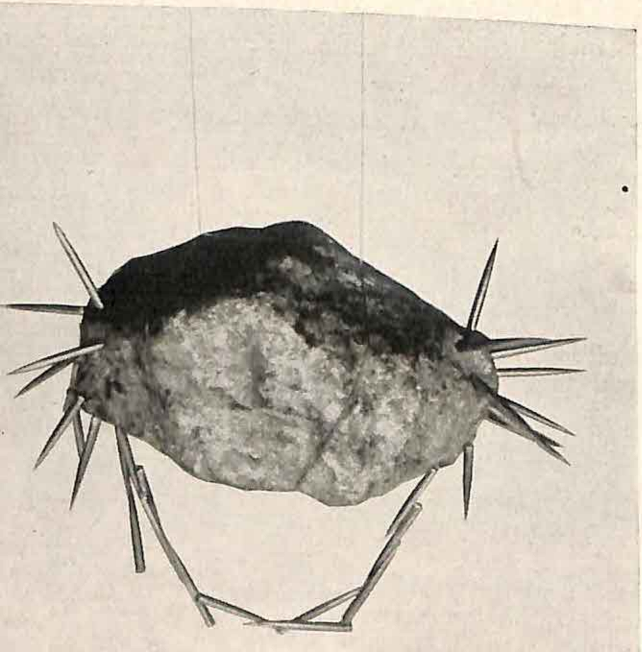


FIGURE 2. A piece of loadstone. Some steel gramophone needles have been attracted by the loadstone and can be seen clustering near the " poles."

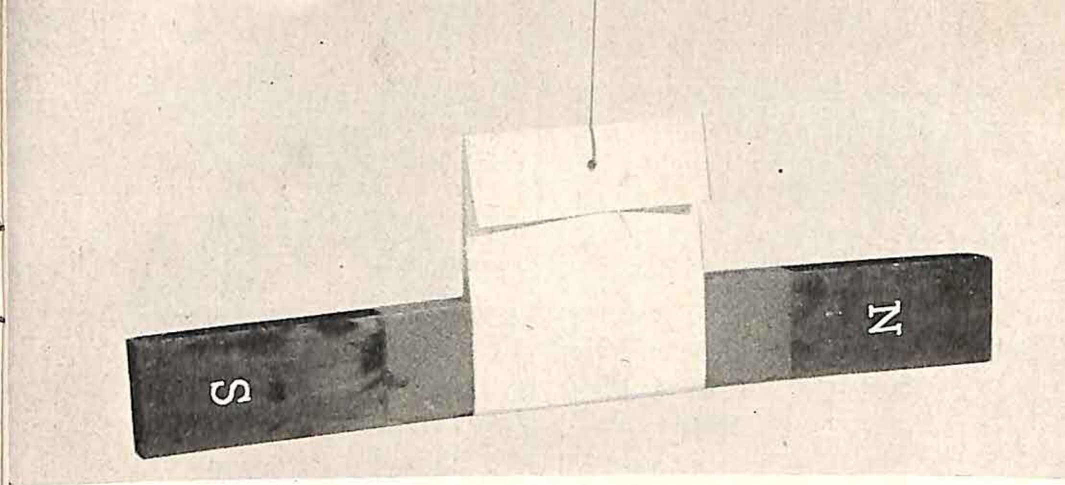


FIGURE 3. This steel bar magnet has been suspended in a paper stirrup. The letters N and S mark the *poles* of the magnet.

When freely suspended both loadstone and a steel magnet come to rest pointing north and south. The end which points to the north is called the *North Pole* and is often painted red. The other end pointing to the south is called the *South Pole* and is painted black.

Problem A: What is Magnetism ?

Question 1. **How can Magnets be Made and Destroyed ?**

In the days of Queen Elizabeth I an Englishman, Doctor William Gilbert, found that he could make a piece of iron " magnetic " by rubbing it many times with loadstone. Nowadays we do not use iron to make magnets if we want them to retain their *magnetization* for a long time ; we use steel instead. Steel is made from iron in such a way that it has in it a small percentage of carbon. It is found that steel retains magnetization much longer than iron, especially soft iron, though it is more difficult to magnetize. There are several ways of rubbing steel with loadstone to produce a magnet. When made, one steel magnet can be used to make more magnets. Permanent magnets are made of steel.

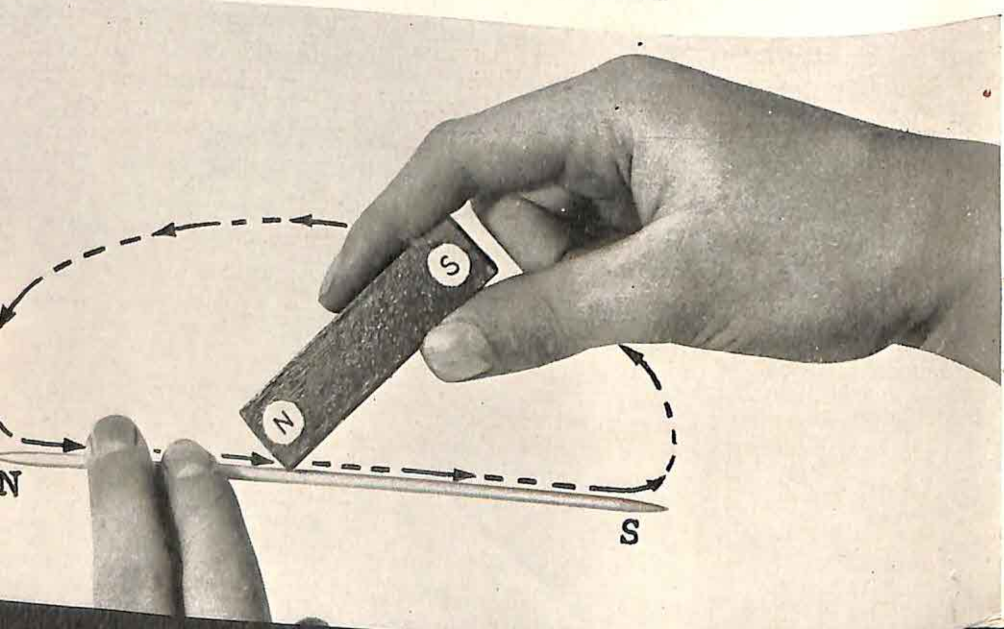
SOME THINGS TO FIND OUT

1. Compare the following ways of making magnets and decide for yourself which method makes the strongest magnet. Place some iron filings in a pile on a piece of paper and dip each magnet you make into the filings. Compare their strengths by observing how many filings remain clinging to the magnets.

You will require four similar steel knitting needles or pieces of steel clock-spring, some No. 26 S.W.G. D.C.C. copper wire, two strong bar magnets, and a $4\frac{1}{2}$-volt battery or a 2-volt accumulator.

(*a*) *Single touch method.* On a table place one of the knitting needles and hold it with your fingers. Stroke the needle with one of the bar magnets, following the arrows shown in Figure 4. Note carefully which pole of the stroking magnet you use and mark the ends of the needle so that you can recognize them.

FIGURE 4. Single touch method.



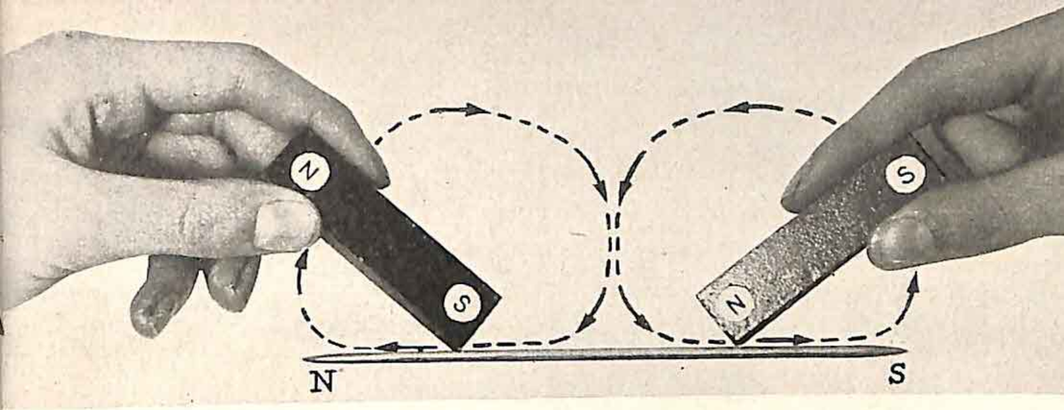
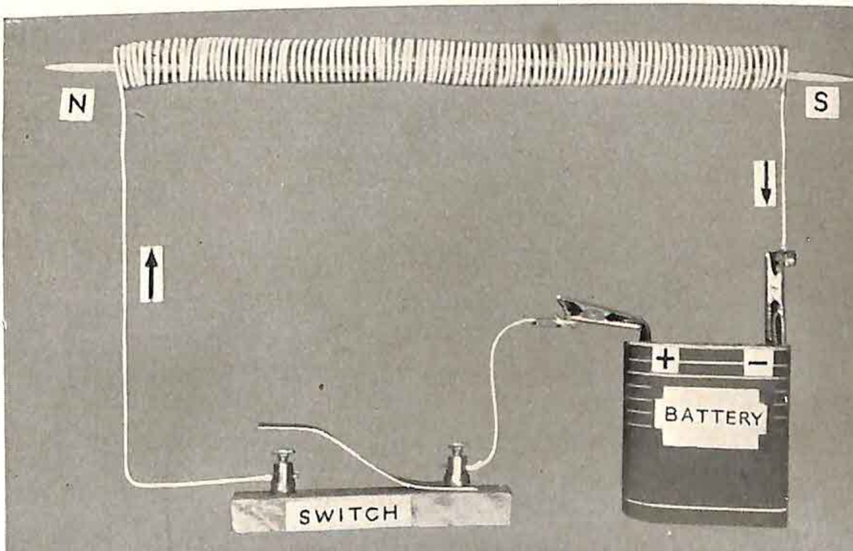


Figure 5. Double touch method.

(*b*) *Double touch method.* Draw two magnets apart, along and towards the ends of your second needle, as in Figure 5. Again note carefully the positions of the poles and the ends of the needle.

(*c*) *Electro-magnetic method.* Make a *solenoid* by winding 100 turns of No. 26 s.w.g. d.c.c. copper wire around a long pencil. See Figure 6. Insert your third needle in the solenoid and switch on a current from the battery or accumulator. Tap the needle for about 20 seconds and then switch off the current. Note carefully in which direction the current flowed round the solenoid. We shall need this information later. Do you agree that Figure 24 is correct ?

Figure 6. Electro-magnetic method.



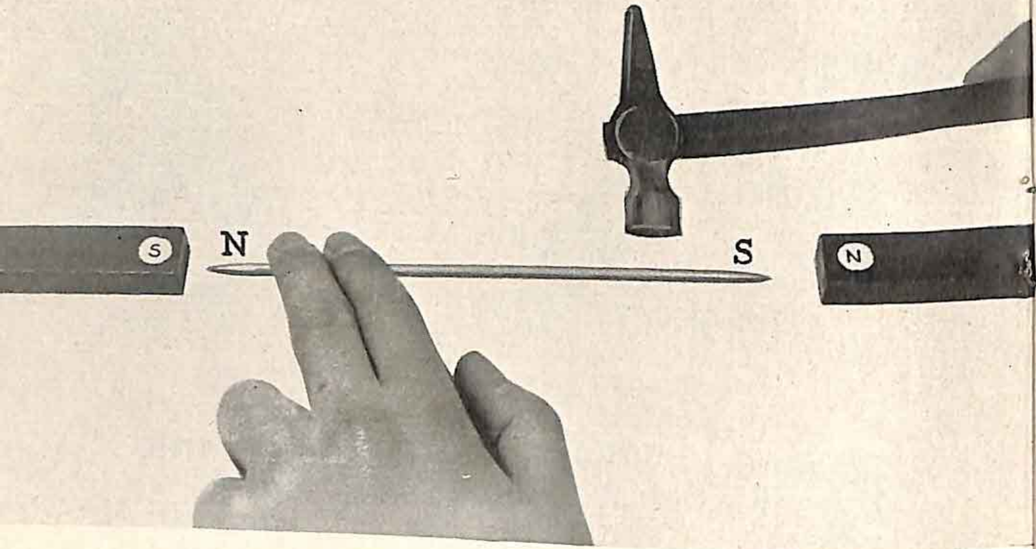


FIGURE 7. Induction method.

(*d*) *Induction method.* Place two strong bar magnets on a table with their opposite poles facing each other, as in Figure 7. Leave a space between them for your fourth needle. Put the needle between the two magnets and tap it gently with a light hammer. Make marks on the needle to indicate which end was close to the north pole, and which end was close to the south pole of the permanent bar magnets.

Now test the strength of each of the four needles with the iron filings. (See Figure 2.) Which needle retains the biggest cluster? Where do the filings cling most strongly? Suspend each needle in a paper stirrup and mark its north and south poles. Do these poles agree with those marked on the photographs? Is the magnetic pole formed at the end of the stroke opposite in kind to the stroking pole?

By means of diagrams record in your notebook the results of these four experiments.

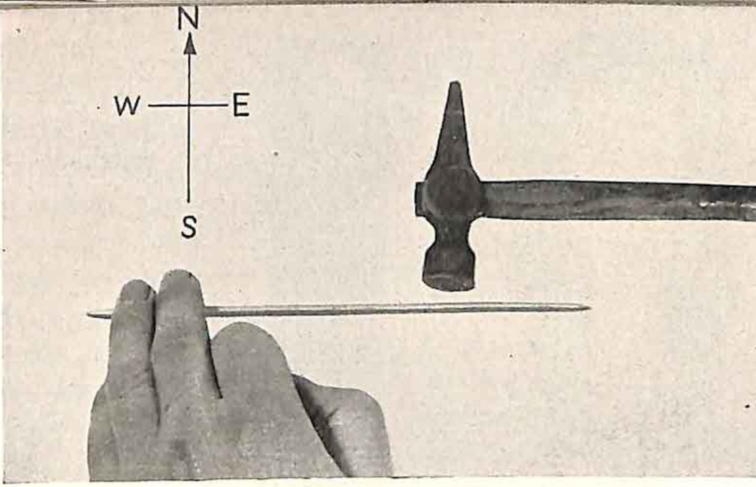


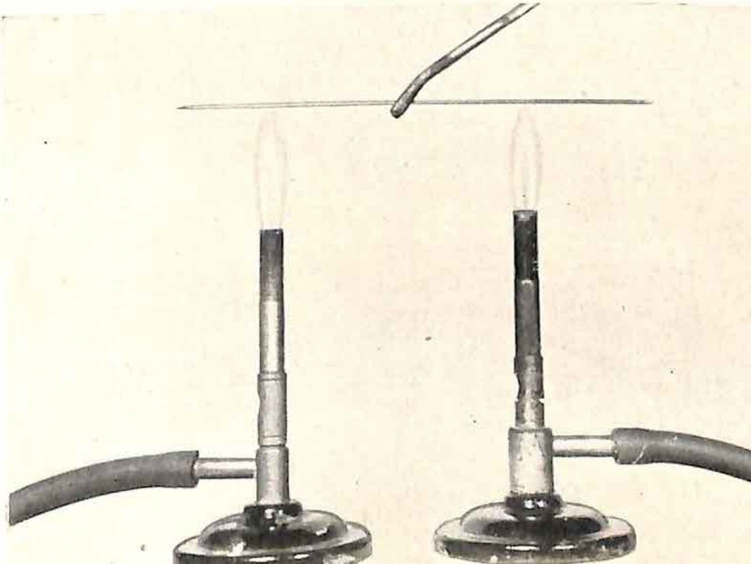
FIGURE 8. Partial destruction of the magnetization.

2. Take one of your magnetized steel knitting needles and lay it in an East and West direction. Strike it sharply several times with a hammer. Now test it again for magnetization with iron filings. Has the strength of the magnet changed?

3. Take another of the magnetized needles. Heat it to red heat in a Bunsen flame, holding the needle in an east and west direction. Allow it to cool and test again with iron filings for magnetization. Does the heat destroy the magnetization?

4. Repeat the experiments to make a magnet using long soft iron nails in the place of the needles. How well do iron filings cling to each of the iron nails?

FIGURE 9. Complete destruction of the magnetization.



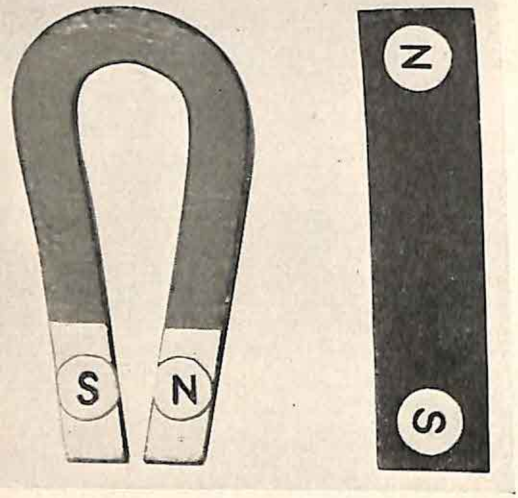


FIGURE 10. Magnets are made in many different shapes. Two of the most useful are the "U" or horseshoe-shaped magnet, and the straight bar magnet.

These experiments show us that :—

(1) there are four ways of making a magnet;
(2) magnetization can be completely destroyed by heating;
(3) steel is harder to magnetize than soft iron, but steel retains its magnetization better.

Problem A: What is Magnetism?

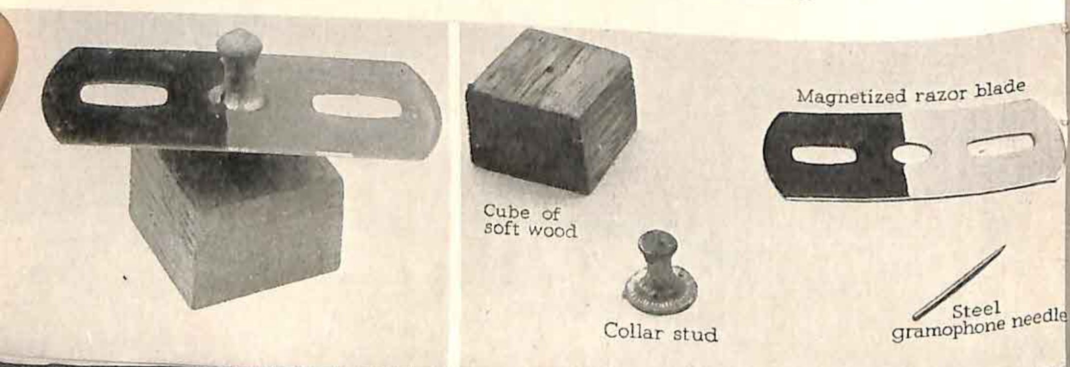
Question 2. **What is a Magnetic Field?**

For several of the following experiments you will want a sensitive magnetic needle that can swivel freely on a pivot. Make one or more for yourself from a double-edged razor blade by magnetizing it and mounting it as in Figure 11. Mark and colour the poles.

SOME THINGS TO FIND OUT

1. Bring up various objects to one of these pivoted magnetic needles. Try copper, perspex, bakelite, wood, glass, nickel, brass, silver, aluminium, iron and steel. Try cobalt too, if you can obtain some. Which of these substances are attracted to the magnet? You will not *feel* the pull on any of these substances because

FIGURE 11. Making a pivoted magnetic needle.

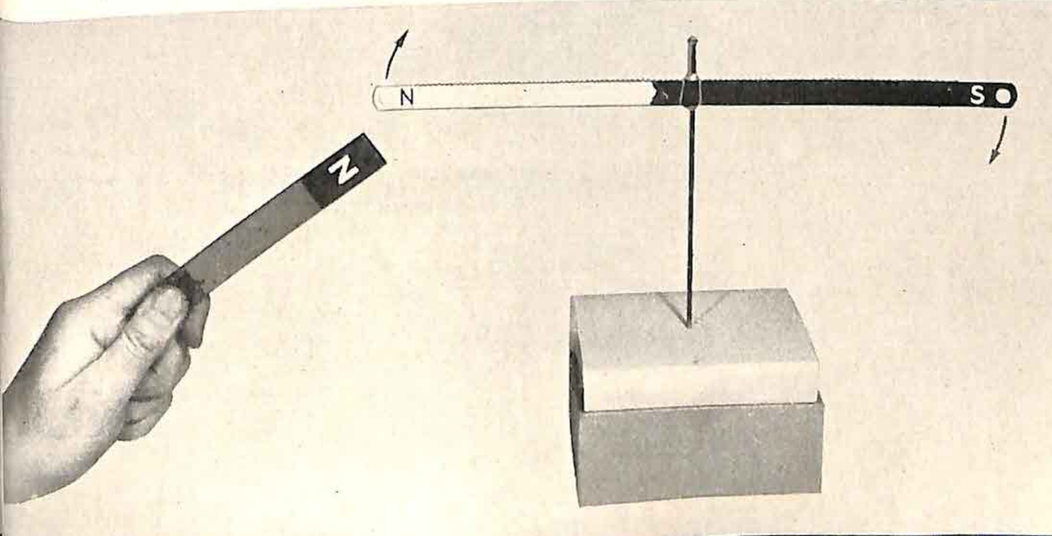


it is so weak, but the needle will turn and thus show that there is attraction.

You will find that the magnet attracts only three substances—iron (including steel), nickel, and cobalt. Magnetic properties are shown, however, by certain alloys of two or more of the metals, iron, nickel, cobalt, chromium, aluminium, manganese, and copper. Cobalt-steel is well-known because it can be strongly magnetized. The aluminium—nickel—cobalt range of alloys, based on the work of the Japanese scientist Mishima, can be used to make strong magnets that will stand a good deal of rough treatment. These are the ALNICO magnets used in schools today.

2. Take a pivoted magnetic needle with its poles N and S clearly and correctly marked on it. You may use your pivoted razor blade, or you may build a larger model using a steel hacksaw blade as shown in Figure 12. Bring the north pole of a bar magnet towards the needle. Do you notice that the north pole of the needle moves away from the north pole of the bar magnet held in the hand, as indicated by the arrow in Figure 12? What happens when the south pole of the bar magnet is presented to the north pole

FIGURE 12. Experiment to show repulsion between two magnetic poles.



of the pivoted needle? Can we state these results in the following way? "*Like* poles (either two norths or two souths) *repel* each other; *unlike* poles (a north and a south) *attract* each other."

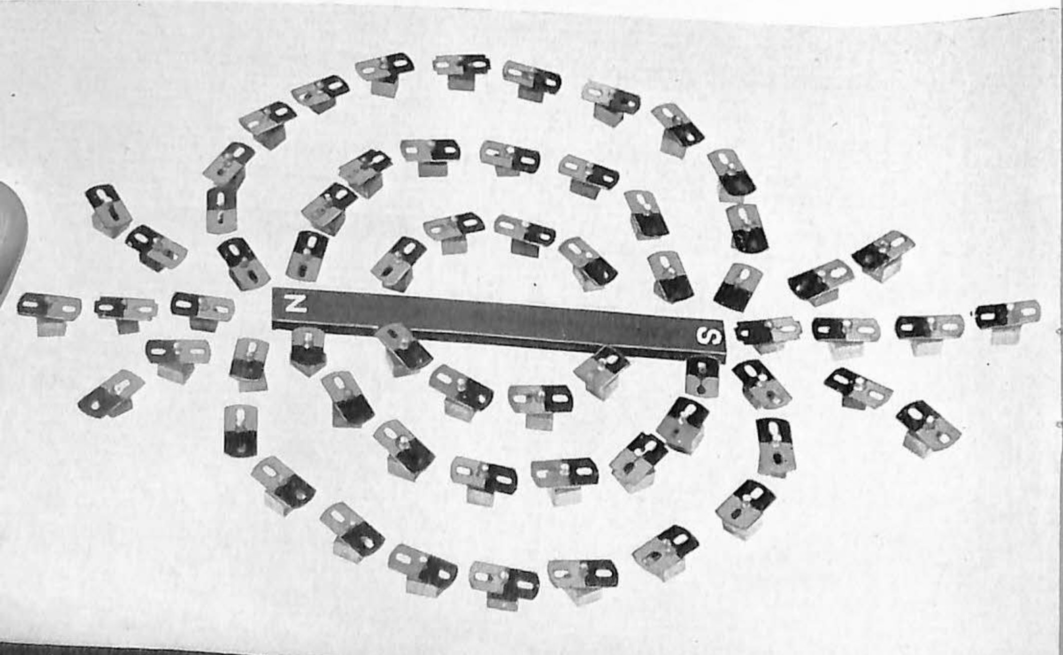
3. Try this second experiment again with a piece of unmagnetized soft iron. Present it to the north pole of the needle. They attract each other. Present it to the south pole. Again they attract each other. There is no repulsion at all in any position. Thus we can say that repulsion takes place only between two magnetic poles. This property can be used to find out whether a piece of iron is magnetized.

The certain test for magnetization is repulsion.

MAGNETIC FIELDS

The space near a magnet in which some magnetic influence can be detected is called the magnetic field of the magnet. There are several ways of detecting such a field. We must remember that the field exists not only on a flat plane but all about in space around the poles of the magnet.

FIGURE 13. Magnetic field shown by using pivoted magnetic needles.



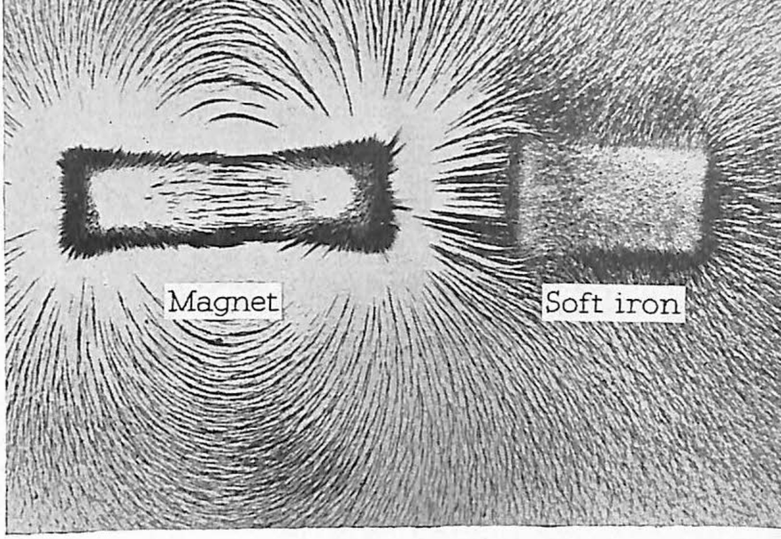


FIGURE 14.

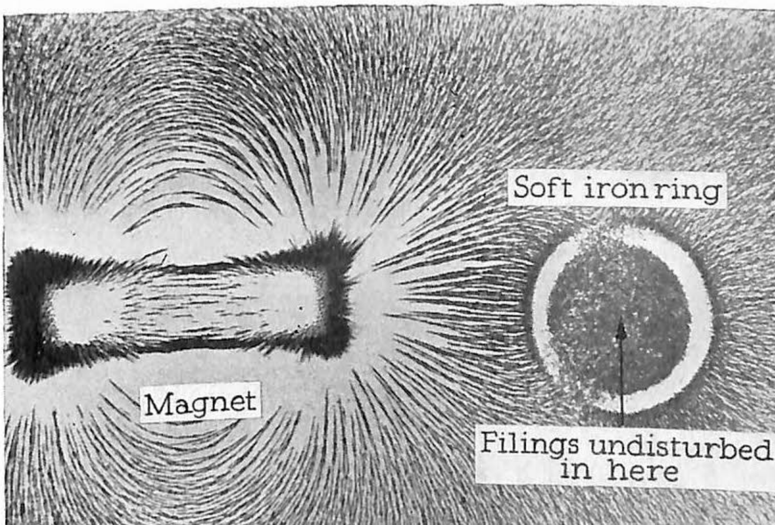
SOME THINGS TO FIND OUT

Map various magnetic fields.

1. *Using pivoted magnetic needles.* Lay a bar magnet on a sheet of paper. Surround it by many pivoted magnetic needles. Join by continuous lines the direction in which the needles set themselves. Repeat this in several different positions. See Figure 13.

2. *Using iron filings.* Lay a sheet of stiff white paper on top of a bar magnet and a piece of soft iron. Sprinkle iron filings on the paper. Tap the paper gently and the filings will set themselves in a pattern. See Figures 14 and 15.

FIGURE 15.



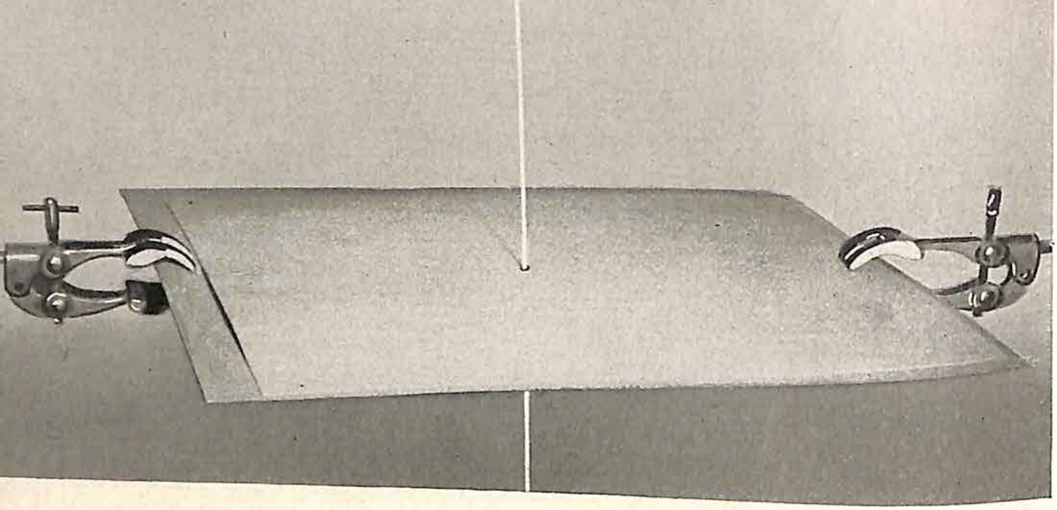
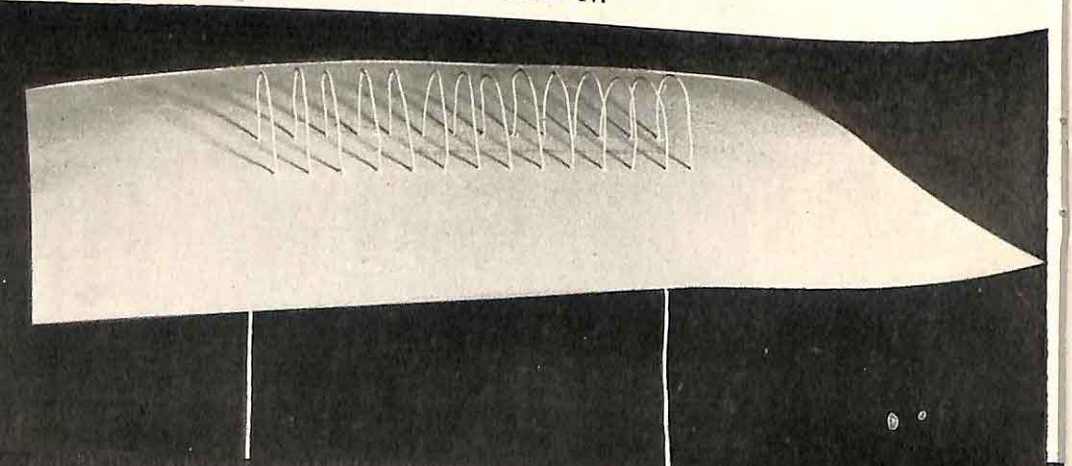


FIGURE 16.

Try the following magnetic fields and record them by sketches in your notebook. You must decide which is the most suitable way of plotting each one. Use:

(*a*) a horizontal long bar magnet,
(*b*) two bar magnets side by side, with like poles in opposite directions,
(*c*) two bar magnets side by side, with like poles in the same direction,
(*d*) a horseshoe magnet,
(*e*) a bar magnet near a piece of soft iron (Figure 14),
(*f*) a bar magnet near a soft iron ring (Figure 15),
(*g*) an electric current flowing in a straight conductor (Figure 16 shows how to look for this field),
(*h*) an electric current flowing through a solenoid (Figure 17 shows how to look for this field).

FIGURE 17.



Now see if you agree with the following observations.

1. The iron filings and the pivoted magnetic needles show lines or directions through the magnetic field from one pole to the other. They indicate the direction a "free" north pole tends to move. (These lines are called *magnetic lines of force.*)

2. The magnetic lines of force outside the solenoid continue also inside the solenoid to form a complete *magnetic circuit.*

3. No two magnetic lines of force cross each other.

4. Soft iron forms an easy path for these magnetic lines of force. When the iron is in the form of a ring, the inside is shielded from magnetic forces.

We must therefore conclude that we can use the idea of a magnetic circuit. Every magnetic line of force starting from a magnetic north pole must trace a path to a magnetic south pole and then continue inside the iron or solenoid to complete the circuit.

Magnets are stored by placing pieces of soft iron, called *keepers*, across their ends close to the poles. In this way the magnetic circuit is preserved.

FIGURE 18. Horseshoe magnet with keeper.

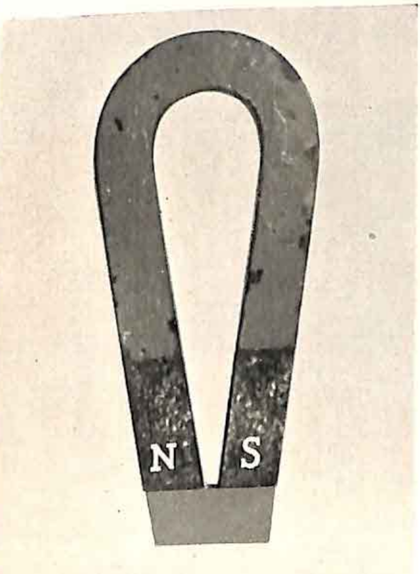
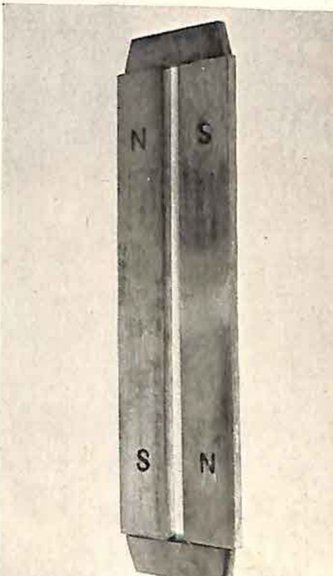


FIGURE 19. Pair of bar magnets with keepers. Notice how the poles are placed.



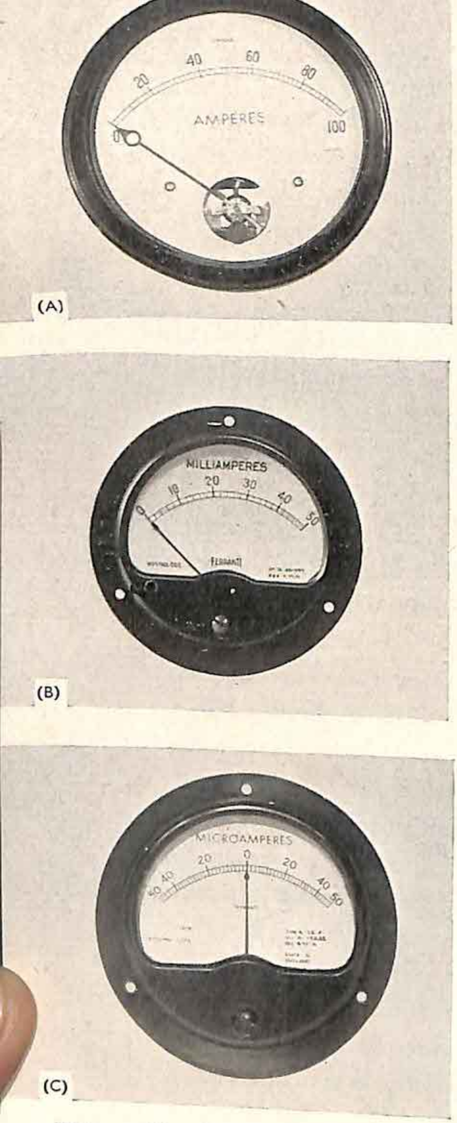
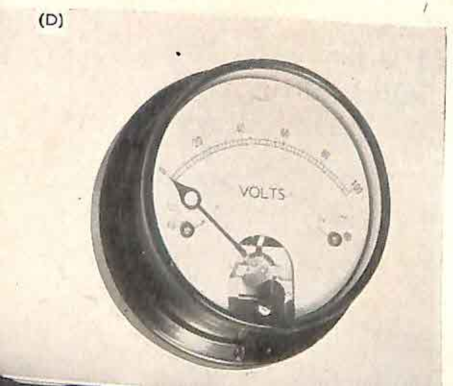


FIGURE 25. Some moving-coil instruments.

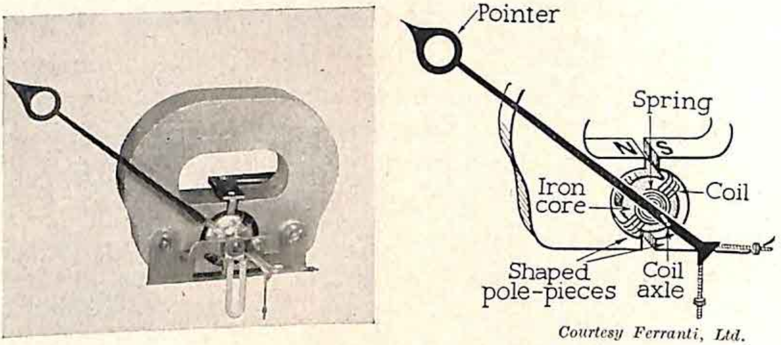
Courtesy Ferranti, Ltd.



Moving-coil instruments. It is possible to wind with very fine wire a small coil. Suspended between the poles of a heavy powerful magnet, it forms a sensitive current-detector. This is known as a moving-coil instrument. These moving-coil current-detectors are delicate but accurate and reliable. Some measure tiny currents of the order of one millionth part of an ampere. We often call these instruments *galvanometers.*

A great variety of moving-coil instruments are designed to measure different currents. Figure 25 shows the dials of some of these meters.

If you were to look inside the meters shown in Figure 25 you would probably be surprised. All of them have the same sensitive current-detectors as shown in Figure 26. The two terminals on the back of each meter are connected to wires. These wires convey the current to and from the coil. The coil is mounted on an axle so that it is free to turn between the shaped pole-pieces of the magnet. If the coil were allowed to turn completely freely, then even a small current would

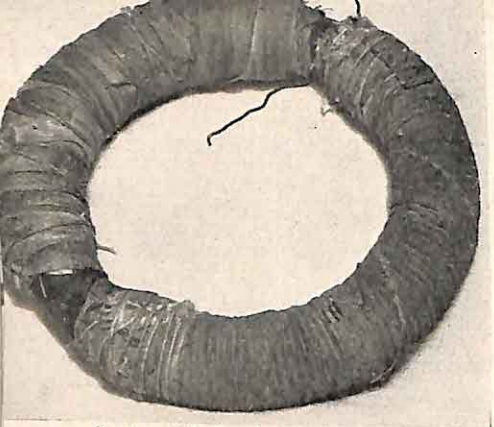


Courtesy Ferranti, Ltd.

FIGURE 26. On the left is a photograph of the inside of a moving-coil instrument showing all the essential parts. On the right is a drawing of the same inside to show clearly the coil, spring, axle, shaped pole-pieces of the magnet, and the pointer.

twist the coil right round and cause the pointer to run off the scale. So a spiral spring is fitted to control the movement of the coil and pointer. The larger the current flowing in the coil, the stronger is the twisting force exerted on the coil, and the further it turns against the spring. The circular iron core and the shaped iron pole-pieces of the magnet leave only a small air-gap in the magnetic circuit. Thus a strong magnetic field is provided for the coil in this narrow air-gap.

How is it possible to use this sensitive current-detector as the basic moving part of all the instruments shown in Figure 25 ? The method is to by-pass much of the current so that only a small fraction of it passes through the actual coil of the current-detector where it is " measured " by noting the reading of the needle. The meter scale is marked so that it indicates the value of the current flowing through the *whole* instrument. That fraction flowing through the current-detector coil is therefore used as a true sample to determine the value of the much larger current passing through the whole instrument.



Courtesy of the Royal Institution of Great Britain

FIGURE 23. Soft iron ring wound with two solenoids, made and used by Michael Faraday himself for his experiments on electro-magnetic induction.

is, he wanted to know if magnetism could produce electricity. So he carefully planned and tried many experiments. He set out to discover if an electric current flowing in one conductor could give rise to an electric current in an entirely different conductor nearby. After much hard work and many failures he eventually wound two separate solenoids on a stout soft iron ring. On connecting one solenoid to a battery, he noticed that a current flowed in the other solenoid for a moment only; on breaking the battery circuit he again noticed that a current flowed in the other solenoid. This was the result Faraday was looking for—and it was a discovery of great importance in the history of scientific progress. The date was 1831. The actual apparatus he used is shown in Figure 23: it can still be seen in the Royal Institution, London.

This success led Faraday to change the details of these experiments. He found that a current was always produced in a long cylindrical solenoid when he thrust a magnet into the solenoid, and also when he pulled it out again.

Faraday had answered this important question: " If electricity can produce magnetism, cannot magnetism produce electricity ? " This discovery led directly to the design of the electric generator and motor, which have together completely changed our standards of living and given us in the twentieth century comforts beyond the wildest dreams of man 100 years ago.

Question I. **How do you make Instruments to Measure Electric Current ?**

Several of our experiments have shown the magnetic effect of an electric current. An electric current flowing in a wire produces a magnetic field which creates forces on the poles of a magnetic needle. These forces, acting in opposite directions, twist the needle. When we made a strong magnetic field, as in Figure 17, we were adding together the magnetic effects of the electric current in many lengths of wire wound into a solenoid.

Imagine yourself looking at one end of a solenoid through which a current is passing. There is a north pole at the end where the current is seen to flow in an anti-clockwise direction. At the other end, where the current flows in a clockwise direction, there is a south pole. The arrows marked on the ends of the letters N and S in Figure 24 help you to remember which way the current flows in the solenoid.

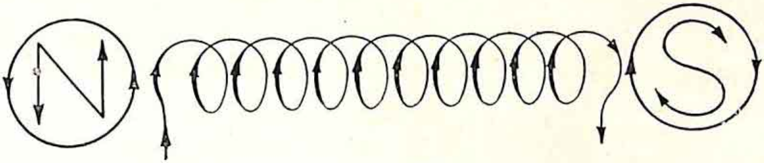


FIGURE 24.

Moving-iron instruments. We have seen in Unit 8 how the solenoid can be used in a direction indicator, and for measuring electric currents.

The early telegraph instrument was built around an electro-magnet. The *polarity* of the magnet was reversed by altering the direction of the electric current.

In these applications the solenoid is fixed and the iron or magnet moves. These are called moving-iron instruments.

So, by using the correct thickness and length of wire as a by-pass, called a *shunt,* this sensitive moving-coil current-detector can be made to measure any strength of current. This is how an ammeter is constructed. The shunt wires in the three instruments A, B and C shown in Figure 25 are placed inside the cases and cannot be seen. Sometimes the shunt wires are mounted outside.

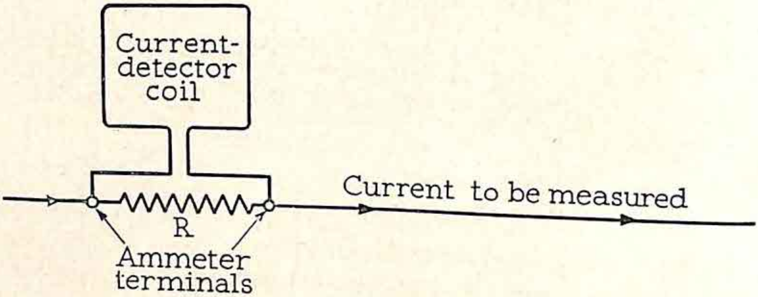


FIGURE 27. Wiring diagram of an ammeter. How a resistor R is connected in shunt with the coil so that much of the main current by-passes the current-detector coil. The movement of the pointer on the scale shows the total current flowing through the complete instrument.

Dial A in Figure 25 shows an *ammeter* measuring a maximum current of 100 amperes. This instrument has a thick, strong shunt wire.

Dial B in Figure 25 shows a milli-ammeter reading to 50 milli-amperes. *Milli-* means a thousandth part. This ammeter has a thinner shunt wire in parallel with the current-detector coil.

Dial C in Figure 25 shows a micro-ammeter reading to 50 micro-amperes. *Micro-* means a millionth part. This ammeter has a fine shunt wire connected in parallel with the coil. The coil and pointer are so arranged that the current can pass through in either direction producing a movement of the pointer to the left or to the right. The zero reading is in the centre.

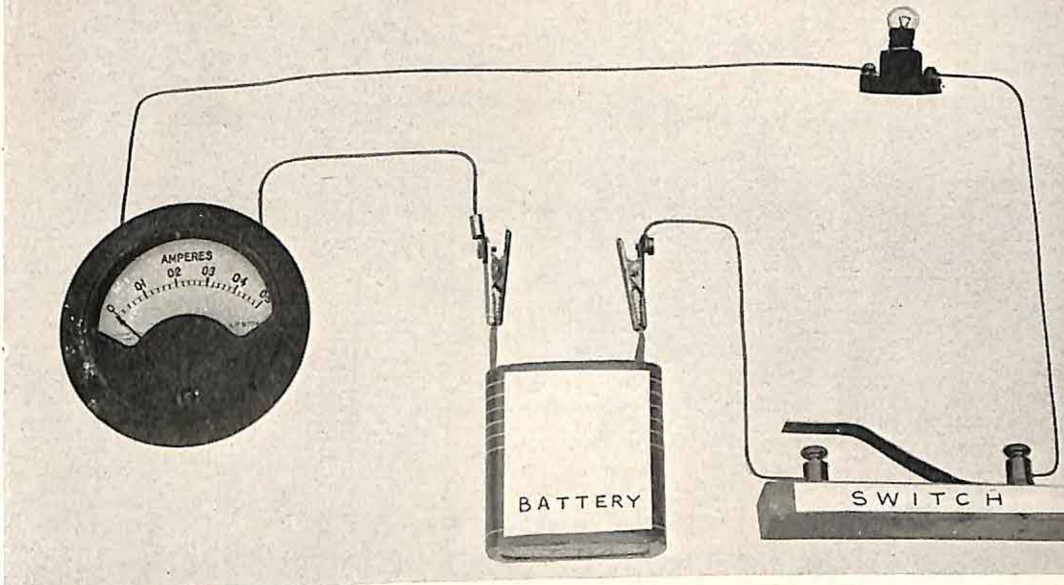


FIGURE 28. How a current-measuring instrument (ammeter) is used to measure the current flowing round a circuit. Notice that the current is made to pass through the ammeter: its shunt is inside its casing.

When you buy a battery the shopkeeper tests it by putting a *voltmeter* across its terminals. He is really measuring the current the battery manages to push through the instrument. The scale is marked in volts to save him the trouble of working out the pressure by the equation

$$\text{CURRENT} = \frac{\text{PRESSURE}}{\text{RESISTANCE}}.$$

Part of the instrument is a resistor, often called a *bobbin*, in series with the coil. (The bobbin may be mounted either inside or outside its instrument

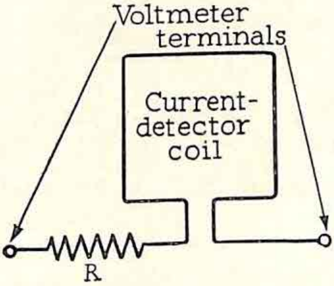


FIGURE 29. Wiring diagram of a voltmeter. How a resistor R is connected in series with the coil so that the pressure of the battery causes a small current to flow through the coil. The scale is drawn so that the pointer indicates the pressure put across the terminals of the instrument.

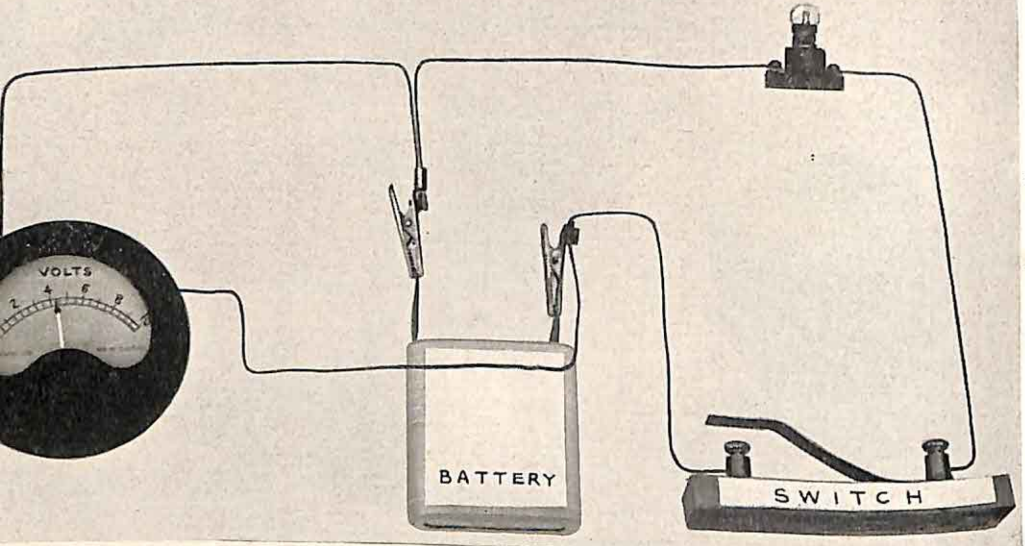


FIGURE 30. How a voltmeter is used to measure the pressure that is needed to drive a current through a bulb. Note that the battery pushes a small current through the voltmeter at the same time as it pushes a different current round the main circuit containing the switch and bulb. The bobbin is inside the casing of the voltmeter. Will the reading of the voltmeter change when the switch is closed and the current starts to flow?

case.) Therefore the circuit he uses consists of battery, resistor, and current-measuring instrument. The value of the resistance of the bobbin chosen depends on the highest pressure the voltmeter is designed to measure.

Dial D in Figure 25 shows a voltmeter reading as far as 100 volts. The coil and resistor of this instrument have a total resistance of 10,000 ohms.

When a pressure of 100 volts is placed across the terminals of this voltmeter, the current flowing through both the coil and the resistor is calculated as follows:

$$\text{Current (in amperes)} = \frac{\text{Pressure (in volts)}}{\text{Resistance (in ohms)}}$$

$$\therefore \text{Current (in amperes)} = \frac{100}{10{,}000} = \frac{1}{100}.$$

Thus this instrument is made to give the maximum reading on its scale when the current is $\frac{1}{100}$th of an ampere.

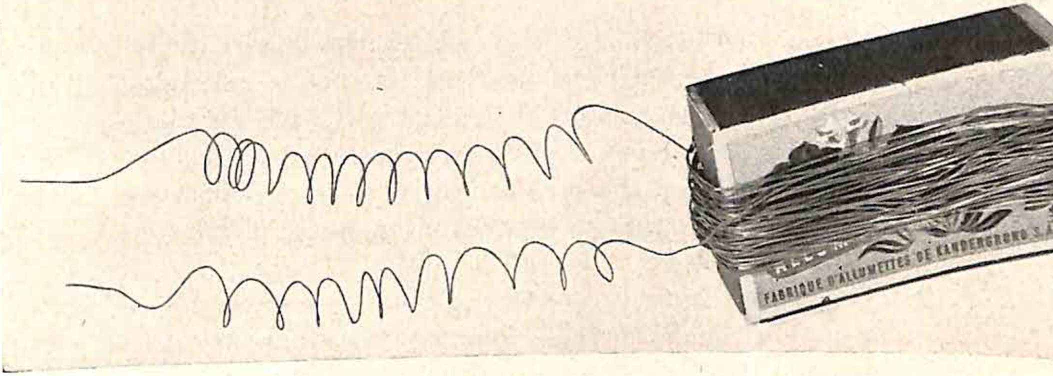


Figure 31. How to wind the coil of wire for your galvanometer.

SOME THINGS YOU MAY CARE TO DO

1. Build for yourself a sensitive galvanometer.

Moving-magnet galvanometer. Wind 100 turns of No. 32 s.w.g. enamelled copper wire round a match box. (Look at top of page.)

Remove the match box and through the centre of one of the long sides of the wire coil insert a needle. Draw the turns together and bind them with adhesive tape to form a compact coil of wire. Magnetize a razor blade and seal on one side of it a fine dried stalk of grass. This stalk of grass acts as a pointer. Mount the razor blade by a collar stud on the point of the needle, and fix the whole to a wooden base. Now the pointer can be balanced by a blob of sealing wax on the other edge of the razor blade.

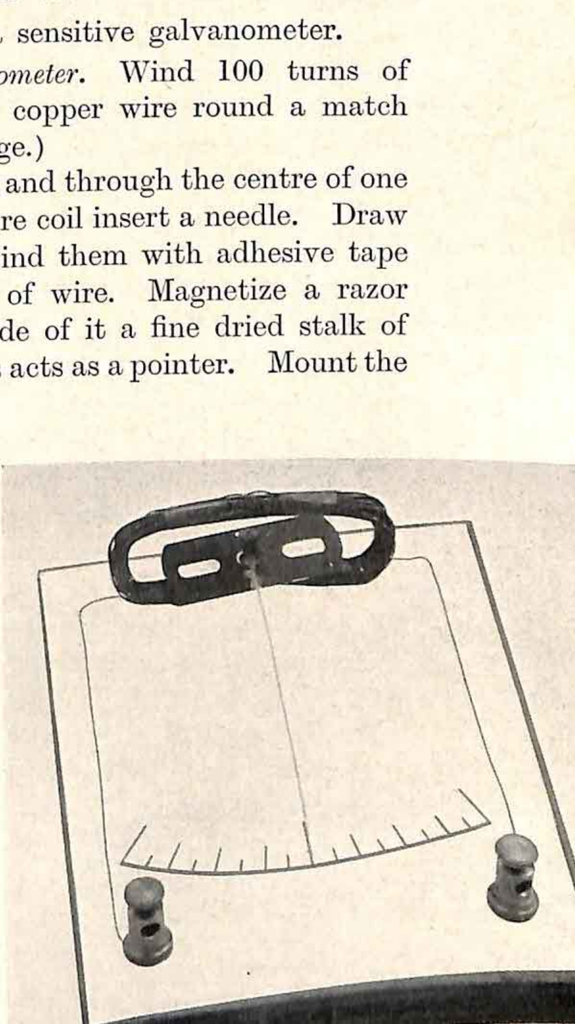


Figure 32. How to mount the coil of wire to form the moving-magnet galvanometer.

Turn the base until the pointer can move freely. Allow the magnetized razor blade to come to rest lying north and south. Turn the coil of wire until its plane lies north and south. Then fix a scale to the base so the pointer is in the middle zero position. Take care to keep the instrument away from magnetic fields that might disturb its balance.

You now have a sensitive galvanometer capable of detecting small currents passing in either direction through the coil of wire.

2. Convert your galvanometer into an ammeter by connecting suitable shunts in parallel. Include your ammeter in series in a circuit with an ammeter which reads correctly. Mark on the scale of your ammeter the positions of the needle for different readings of the current. Your ammeter will now read correctly the current in amperes. A suitable circuit might be a motor-cycle accumulator connected to a head-lamp bulb. Then convert your galvanometer into a voltmeter by connecting suitable bobbins in series.

3. Set up the circuit shown in Figure 28. Note the reading of the ammeter when it is steady. Connect 4 inches of No. 26 s.w.g. eureka wire as a shunt in parallel across the terminals of the ammeter. Explain why the reading of the ammeter changes.

4. Set up the circuit shown in Figure 30. Note the reading of the voltmeter when it is steady. Connect as a shunt in parallel across the terminals of the voltmeter various lengths of No. 26 s.w.g. eureka wire. Explain why the voltmeter readings change. Now disconnect one wire leading to the voltmeter and insert a 100-ohm resistor in this lead. Replace it by a 1000-ohm resistor in the lead. What difference do you notice each time in the voltmeter readings? Why is there a difference?

Question 2. **Can a Magnet be used to Generate Electricity?**

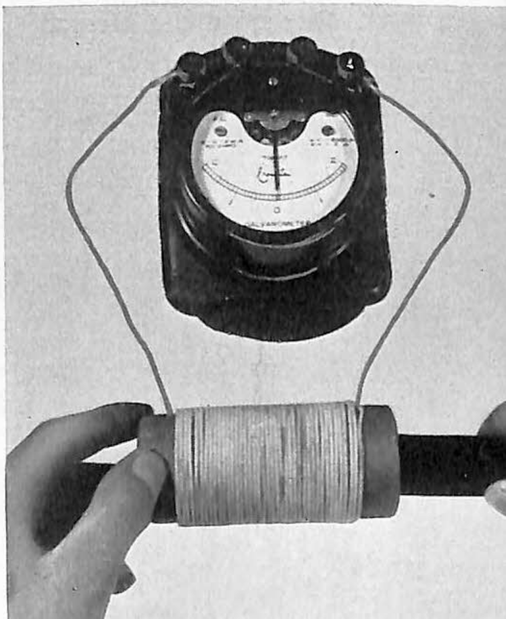
To answer this question we can perform a number of short simple experiments. From these we shall be able to rediscover the facts and principles first observed about the same time by Faraday in England and Henry in America.

SOME THINGS TO FIND OUT

1. You will require a strong bar magnet at least 3 inches long. Wind a solenoid of 150 turns of No. 26 S.W.G. D.C.C. copper wire on a former which fits easily round the magnet. Connect the solenoid to your sensitive galvanometer which can indicate a current flowing in either direction. Carry out the following operations and note the maximum flick of the galvanometer needle. Figure 33 shows how to hold the solenoid and the magnet. Your galvanometer will work just as well as the one shown here.

(*a*) Hold the magnet at rest outside the solenoid.
(*b*) Move the magnet into the solenoid.
(*c*) Hold the magnet at rest inside the solenoid.
(*d*) Pull the magnet out of the solenoid.
(*e*) Push the magnet rapidly into the solenoid.
(*f*) Jerk the magnet rapidly out of the solenoid.
(*g*) Reverse the magnet and repeat all the above operations again.

FIGURE 33. How an electric current is generated by moving a magnet in and out of a solenoid.



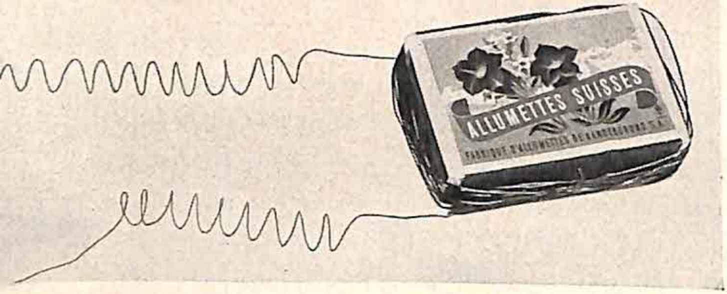


FIGURE 34. How a compact coil of 100 turns of wire can be wound on a match box.

2. Connect another piece of wire to the solenoid and wind on another 150 turns in the same direction. Now repeat everything you did in the last experiment. Have you succeeded in generating electricity by moving the magnet in and out of the solenoid ?

3. Wind a small compact coil of 100 turns of No. 32 S.W.G. enamelled copper wire round a match box. Remove the match box and bind the coil of wire with adhesive tape so that it can be handled easily. Now connect it to your sensitive galvanometer. Fix two opposite poles of two strong permanent bar magnets about an inch apart. (See Figure 35.) Repeat the operations of the first experiment, moving the coil of wire into and out of the magnetic field between the two poles. (The coil of wire is really a solenoid that has been compressed.) Do you find the same results ?

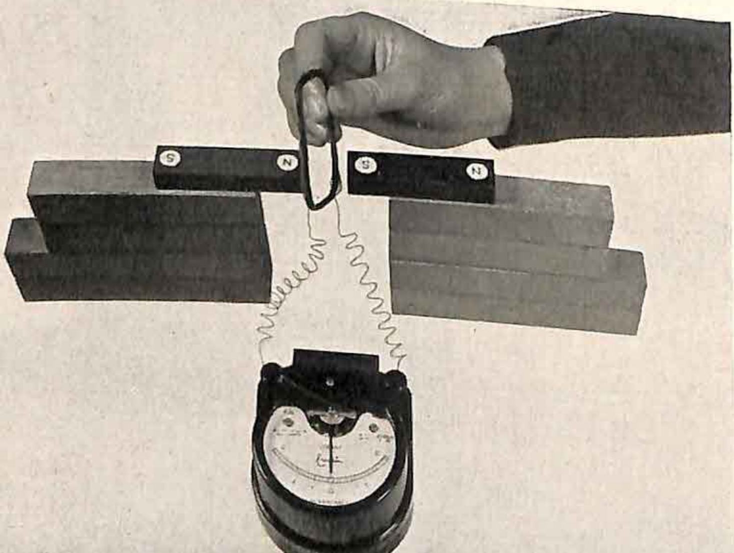


FIGURE 35. How an electric current is generated by moving a coil of wire in and out of a strong magnetic field.

Examine the results of these experiments. Magnetic lines of force trace paths between the poles and in the space surrounding a magnet. When the magnet is some distance away, few of the magnetic lines of force pass through the turns of the solenoid. When the magnet is in the solenoid most of the lines of force pass through the turns of the solenoid. In both cases no current flows through the galvanometer.

A current only flows when the magnet, or magnetic field created by the magnet, is moving relative to the solenoid, that is, when the number of magnetic lines of force passing through the turns of the solenoid is changing, either increasing or decreasing. The faster this increasing or decreasing takes place, the greater is the current. The same principles apply in all the experiments.

We call this an *induced current* and say that it is caused by an *induced electro-motive force* in the solenoid. It does not matter whether the number of magnetic lines of force passing through the solenoid is increasing or decreasing as long as the number of them is changing. It is the *rate* at which they are changing that determines the strength of the induced electro-motive force. An increase causes the induced electro-motive force to be in one direction ; a decrease causes it to be in the other direction. That is why we used a galvanometer whose needle could move in one direction or the other.

SOMETHING YOU MAY CARE TO DO

Make a more detailed study of the life and work of Michael Faraday, who lived from 1791 to 1867. See what you can find out about him in the library.

Question 3. **How do Electric Generators work?**

We learned in the last question how to produce electricity by changing the magnetic field passing through the turns of a solenoid. Is it possible to produce a continuous supply of electricity by continuously changing the magnetic field passing through a solenoid ?

To investigate this, a coil of wire is mounted on a pencil, to serve as an axle on which it can be twisted quickly and easily. The two magnets, forming the magnetic field, are pulled apart so that the coil can revolve between them without touching either. Figures 36 to 42 are flash photographs taken to show the same coil and needle of the galvanometer at various points during one complete turn. The coil was turned very evenly while the photographs were taken.

In Figure 36 the coil is lying in such a way that as many as possible magnetic lines of force pass through it. As the coil turns about this position the number of magnetic lines of force passing through it hardly changes at all. The galvanometer needle shows that no current is flowing.

In Figure 37 the coil has already turned a little way round, and its wires are cutting the magnetic lines

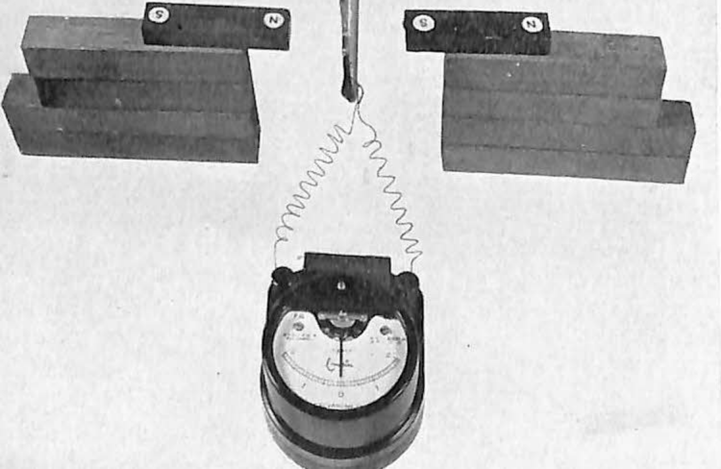


FIGURE 36.

of force. A current is therefore generated and the needle of the galvanometer indicates this current. It is in a position between Figure 36 and Figure 38.

In Figure 38 the coil does not cut any magnetic lines of force. A slight movement of the coil around this position causes the biggest change in the number of magnetic lines of force passing through it. In fact, the magnetic lines of force flow through the coil in a certain direction just before the coil reaches this position, and flow through it in the opposite direction just after it passes this position. Thus there is a rapid change in the number of magnetic lines of force flowing in one direction. This change causes a large current to flow through the galvanometer.

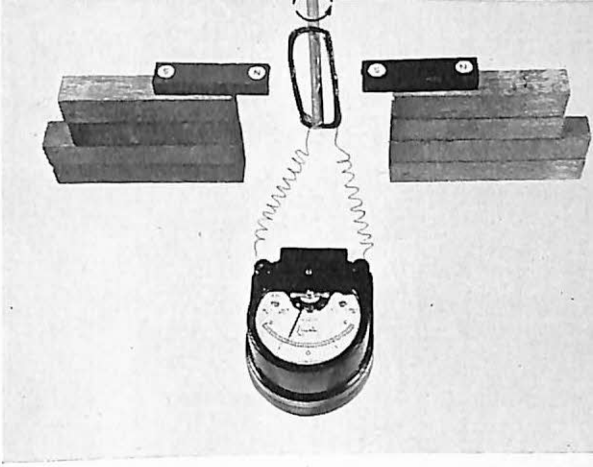


FIGURE 37.

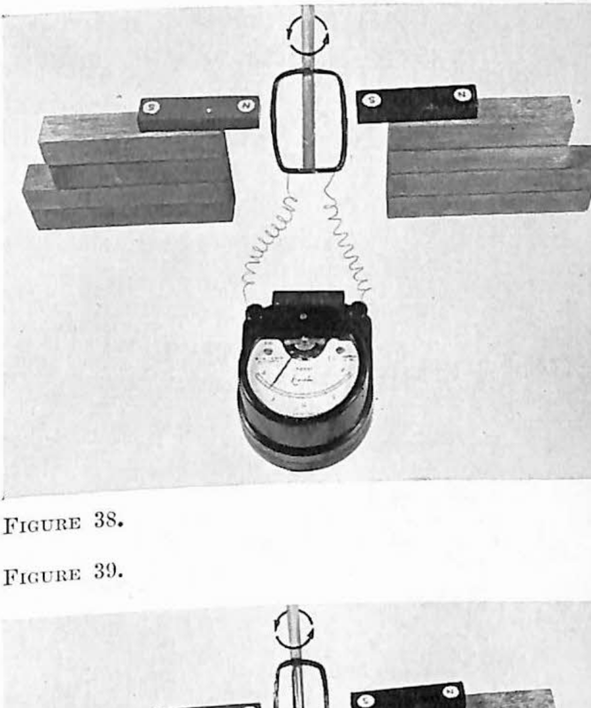
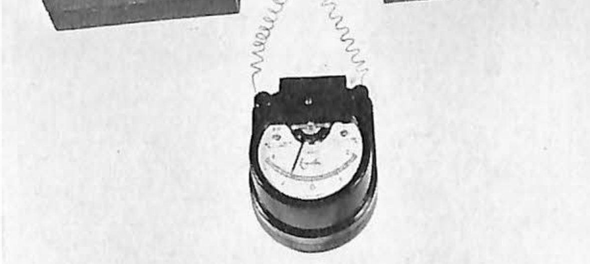


FIGURE 38.

FIGURE 39.



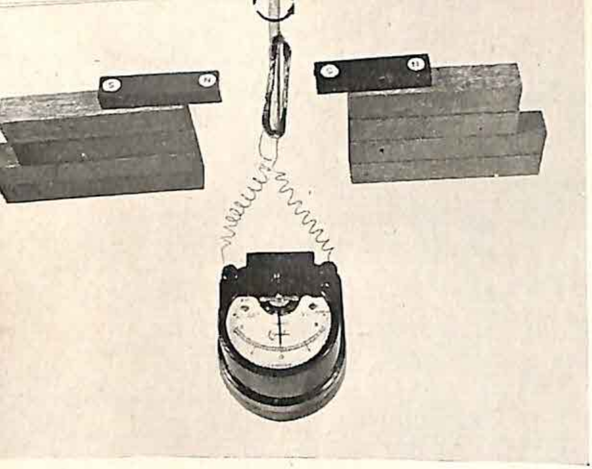


FIGURE 40.

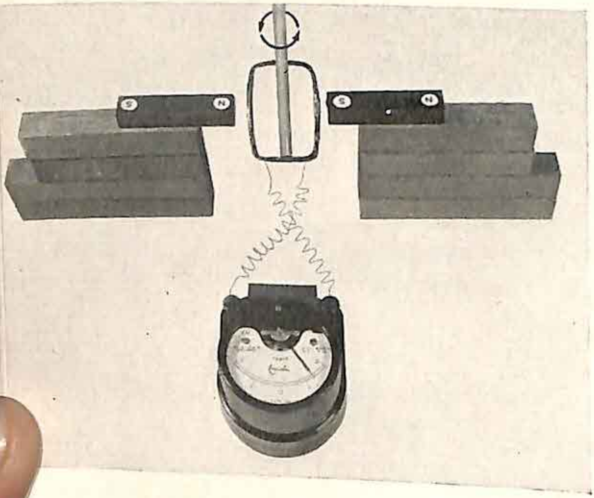
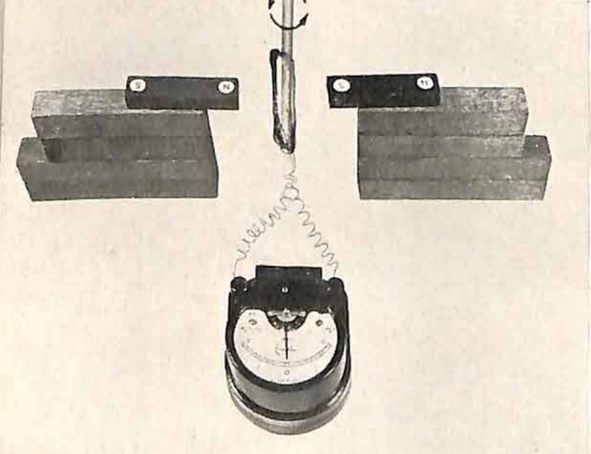


FIGURE 41.

FIGURE 42.



In Figure 39 the turning coil is again cutting fewer magnetic lines of force than in the last position. It is in a middle position between Figure 38 and Figure 40. The current flowing through the galvanometer has become smaller, as you can see in the photograph.

In Figure 40 the coil has revolved still further and is now lying in a similar position to that in Figure 36. In this position there is once more no change in the number of magnetic lines of force passing through the coil. Therefore no current flows.

The next middle position of the coil has not been photographed.

In Figure 41 the coil has turned on so that it lies in a similar position to that in Figure 38, except that it is reversed. There is another very rapid change in the number of magnetic lines of force passing through the coil as it turns past this position. This time the lines change in the opposite direction, so the current flows in the opposite direction too.

The next intermediate position has also not been photographed, and in Figure 42 the coil has now made one complete turn and is back again in exactly the same position as it occupied in Figure 36. Do you notice that the wires leading to the galvanometer have become twisted?

If you follow carefully these flash photographs in the order in which they were taken, you will understand how a small electric *generator* works and also how the current it produces changes. You will see that as a coil of wire turns in a magnetic field an induced electric current is generated, and that this current reverses its direction twice during every turn or revolution. It is an *alternating current* (A.C.). One complete revolution of the coil causes the current to start from zero, rise to a maximum in one direction, fall to zero, rise to a maximum in the other direction, and fall once more to zero. This is called a *cycle*. The number of cycles performed every second by such a current is called its *frequency*.

All electric generators produce electricity by the spinning of a coil in a magnetic field, or by the spinning of a magnetic field inside a coil.

SOMETHING YOU MAY CARE TO DO

Use a coil of wire made like the one in Figure 34, two strong magnets, and your own sensitive galvanometer to obtain similar results to those shown in the photographs (Figures 36 to 42). You will have to keep your galvanometer steady, so it is better to use it in a glass cover to keep it away from currents of air. Note the end of the movement of the galvanometer needle for each position you try. Rapidly jerk the coil through the positions you are investigating.

Alternating current generators or alternators. Before the small generator described in this question can be of real practical use we must find a way of preventing the wires from becoming twisted. At the same time we must be able to take the induced current away from the rapidly turning coil. Such an arrangement is provided by two *slip rings* and *brushes.* The two ends of the coil are connected to two circular metal rings, slip rings, mounted close to each other on the axle of the coil. The rings are insulated from each other and from the axle. Metal or carbon brushes take away the electric current to the external circuit.

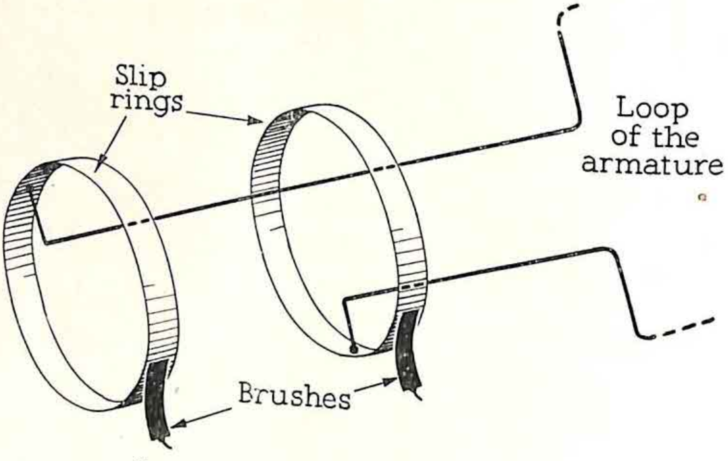


FIGURE 43. Slip rings of an alternator.

A much stronger magnetic field can be obtained if the space left inside the coil is filled with soft iron, and if the poles of the magnets are shaped to leave only a small air-gap between them and the revolving

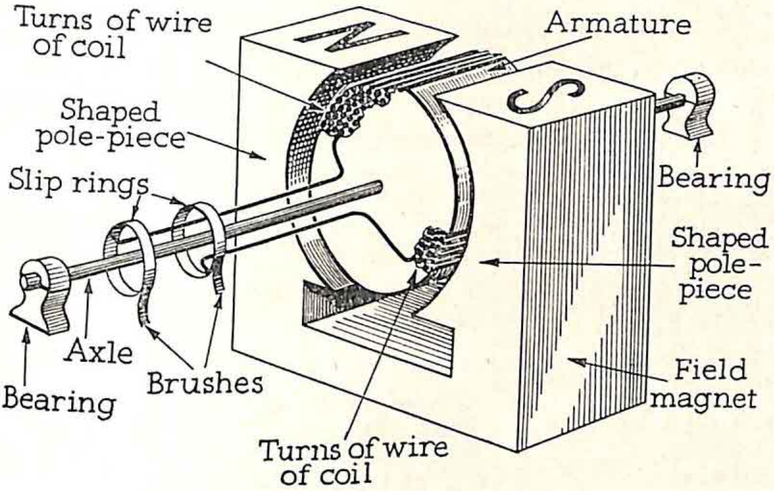


FIGURE 44. A simple alternator.

coil. The coil and the iron core are together called the *armature.* The magnetic poles which provide the field are called *field poles*; they may be at the ends of a permanent magnet or of an electro-magnet.

Large generators have many pairs of field poles, and hundreds of turns of wire are wrapped together to form the armature. Large currents cannot be conducted away easily by brushes from slip rings, so the armature is kept stationary and the field poles are made to revolve. An armature of this type is a *stator*, and the revolving field poles a *rotor*. A small electric current is passed from a direct current dynamo, an *exciter*, through slip rings to the electro-magnets that magnetize the field poles of the rotor.

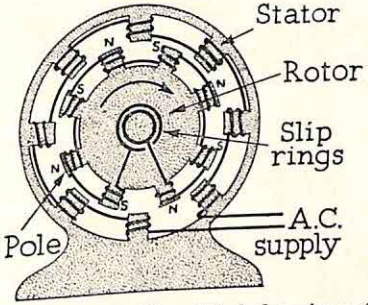


FIGURE 45. Simplified drawing of a big generator. There may be many more poles than the eight shown here.

Enormous A.C. generators are built in an attempt to satisfy the growing demand for electricity in factories and homes. The energy of coal, oil, water, and the nucleus of the atom is used to drive the turbines that turn these generators. The generator or alternator converts the mechanical energy of the turbines into electrical energy. Figure 46 shows clearly the rotor, stator, and exciter in one of these large alternators.

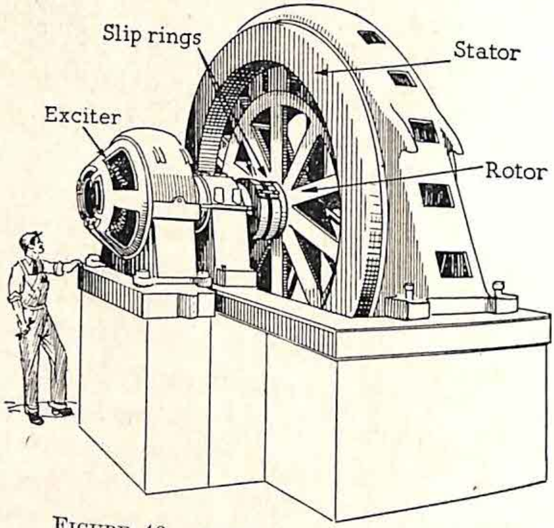


FIGURE 46. A 3000-volt A.C. generator.

A modern alternator is often enclosed in a large casing so that it is not so easy to see these parts.

SOME THINGS YOU MAY CARE TO DO

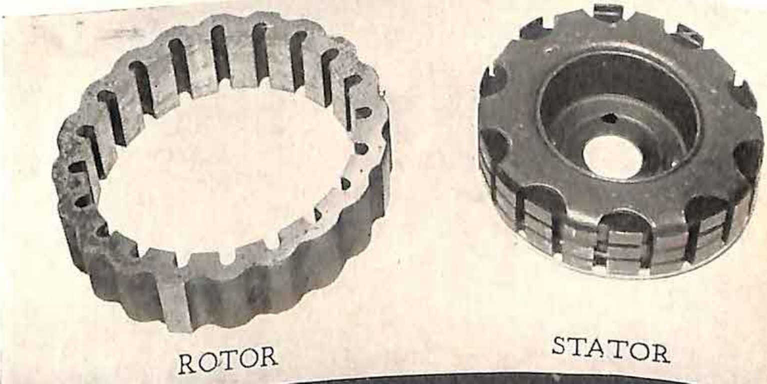
1. Examine a rim generator used on a bicycle wheel. Take it to pieces. The rotor is a strong circular permanent magnet. As you separate the rotor from the stator it is wise to slide a keeper on to the rotor. (The keeper can be an open pair of pliers.) This will sustain the strong magnetic circuit of the rotor whilst

you are examining it. The stator has coils of wire, a soft iron case, and soft iron pole-pieces. Note how the connections are made.

Put the generator together again and connect it to your sensitive galvanometer. Turn the rotor slowly by hand and try to detect that it delivers A.C. Jerk it quickly. Can the needle of the galvanometer respond to the current alternations ? Replace the galvanometer by a small flash-lamp bulb. Does the bulb flicker as you spin the pulley wheel ? Make a sketch of this type of alternator.

2. Study carefully the photographs in Figure 47 of the essential parts of an alternator mounted in the hub of a bicycle wheel. Make a detailed sketch of these in your notebook. Do not take the alternator to pieces, because you would have difficulty in keeping small filings of iron from the powerful multipole magnet, and also because this magnet loses its strength if separated from the central core which acts as a "keeper." In this type of alternator the stator consists of the iron core and coils of wire. The rotor is the field magnet. How many poles are there ? How many times in every revolution of the cycle wheel does each magnet pole come close to a shaped end of the central iron core ? Lift a cycle wheel which has a Dyno-hub fitted, turn it gently with one finger, and so verify that you are correct. Look for the terminals connected to the coils of the stator.

FIGURE 47. Raleigh cycle Dyno-hub. The two terminals connected to the coils of the stator are on the other side and cannot be seen in this photograph.



Direct current generators or dynamos. The alternator which we have studied can be modified to produce direct current (D.C.) electricity.

For certain purposes A.C. cannot be used and D.C. is essential. For instance, it is possible to use D.C. electricity to charge a motor-car battery, and then the battery can provide D.C. electricity to operate all the electrical equipment of the car. It is not possible to do this with A.C. Many electric locomotives require D.C. as this can be simply and easily controlled. A.C. electric locomotives are now constructed but their speed regulation is complicated.

Exactly the same armature and magnetic field are used in the dynamo (D.C.) as in the alternator (A.C.). The difference lies in the method of leading the current out to the external circuit. The current surges back and forth in the armature coil. Thus by switching over the connections from the spinning coil just when the current flow is at a minimum the electricity is made to pass always in the same direction. For this switching a split metal cylinder is used which is insulated from

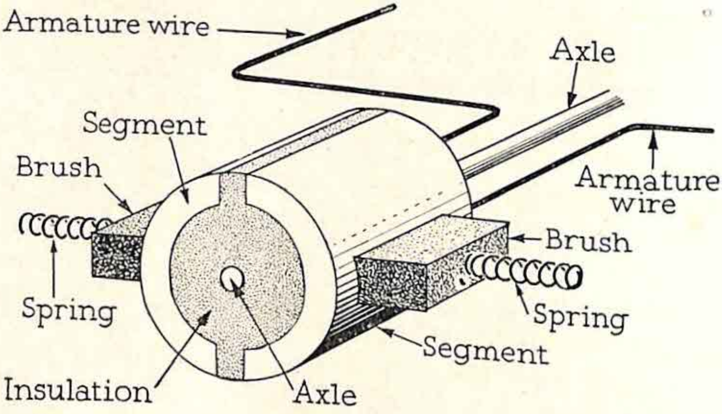
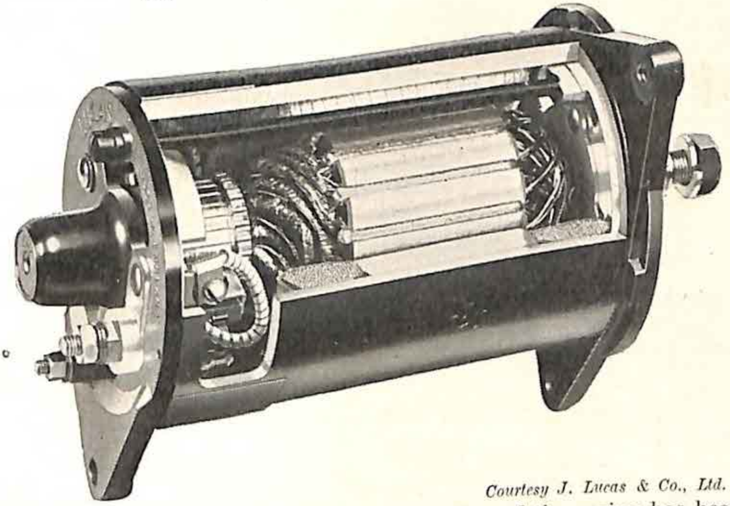


FIGURE 48. A two-segment commutator for direct current dynamos (and motors).

and turns with the armature axle. Brushes are set against opposite segments of this cylinder. The whole arrangement is called a *split ring commutator*. In this way each brush has electricity flowing through it in one direction only.

Some dynamos have 4 or 8 or even 16 different coils of wire wound on the armature and connected to 8 or 16 or 32 segments of the commutator; in these cases the total current delivered is nearly steady with little "ripple" at all. The field magnets on these dynamos are usually excited by means of some of the current supplied by the armature itself.



Courtesy J. Lucas & Co., Ltd.

FIGURE 49. A motor-car dynamo. A section of the casing has been cut away to show some of the parts used in its construction.

SOMETHING YOU MAY CARE TO DO

Examine a motor-car dynamo. Take off dust cover to expose the commutator. How many segments are there? How many brushes can you see? Of what are the brushes made? Can you see the springs holding the brushes against the segments? Why must you replace the dust cover carefully after inspection?

Question 4. **How do Electric Motors work ?**

The general construction and parts of an electric motor are almost identical with those of a generator. In fact, direct current dynamos and motors are often interchangeable. These machines act as dynamos when mechanical energy is converted into electrical energy, as motors when electrical energy is reconverted into mechanical energy. These *dyna-motors*, as they are sometimes called, are most convenient because of the double rôle they play. Installed on electric trains, trolleys or trams they act as motors when climbing uphill, drawing electricity from the conductor rail. When descending they act as dynamos, returning electricity to the rail and at the same time braking the motion.

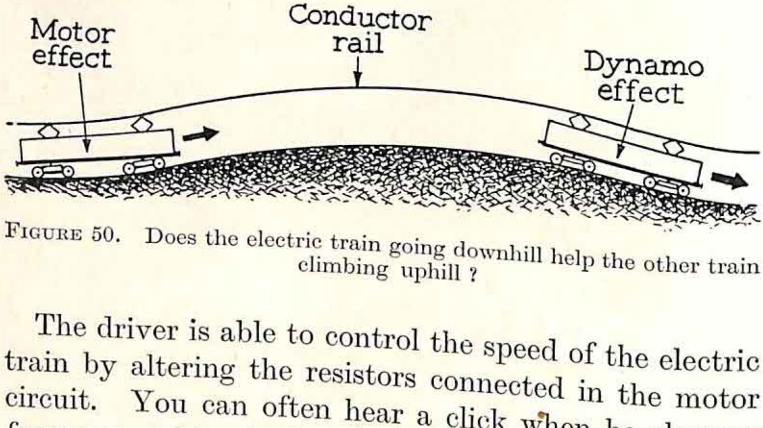


FIGURE 50. Does the electric train going downhill help the other train climbing uphill ?

The driver is able to control the speed of the electric train by altering the resistors connected in the motor circuit. You can often hear a click when he changes from one resistor to the next as the train gathers speed. In the same way he can control the braking force when they act as dynamos by varying the value of the resistors in the circuit. These resistors are often mounted in a train below the floorboards so that they can quickly dissipate their heat.

Direct current electric motors. An electric motor is built in the same way as a dynamo. In order to continue turning the motor must have certain essentials.

(1) The armature must be free to rotate easily.

(2) There must be a strong magnetic field.

(3) The direction in which the current flows round the coil from the main supply must be reversed as soon as the "no twist" or "dead" position is reached. The motor's "no twist" position is the same as the generator's "no current" position. See Figures 36, 40, and 42.

(4) The armature must be heavy enough to overshoot the "no twist" position once it is rotating.

These conditions are provided for as follows:

(1) The armature is mounted on an axle running on smooth bearings.

(2) The magnetic field is created between shaped pole-pieces. The armature is made of soft iron and of such a size that it leaves the smallest possible air gap. See Figure 44. An electro-magnet can be made stronger than a permanent magnet and is often used to create the magnetic field. Some of the D.C. supply can be used for this electro-magnet.

(3) A split ring commutator is used as in the D.C. generator or dynamo. See Figure 48.

(4) The armature is made of soft iron so that it has enough weight to enable it to overshoot the "no twist" position.

Examine Figure 51 carefully. You will notice that at position (*a*) the current passing through the coil from the positive terminal creates a magnetic north pole on the face pointing upwards, and a magnetic south pole on the face pointing down. (See Figure 24.) The attraction and repulsion of these two poles on the poles of the field magnet will cause the coil to turn round on its axle.

When position (*c*) is reached the unlike poles cannot move any nearer to each other. Thus they have arrived at the "no twist" or "dead" position. At this precise moment the commutator changes the direction of the current and then the whole process is repeated. In practice many turns of wire are used for each coil and on the bigger motors there are many such coils and there are many segments on the commutator.

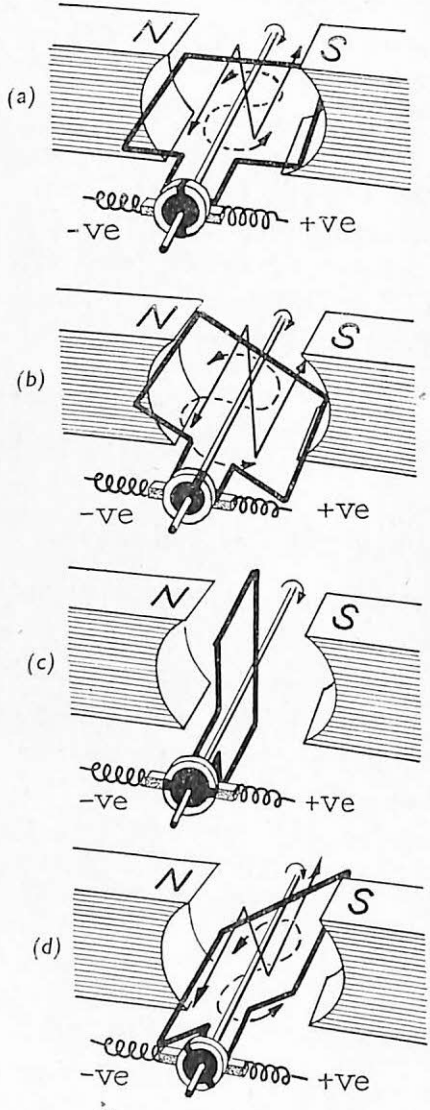
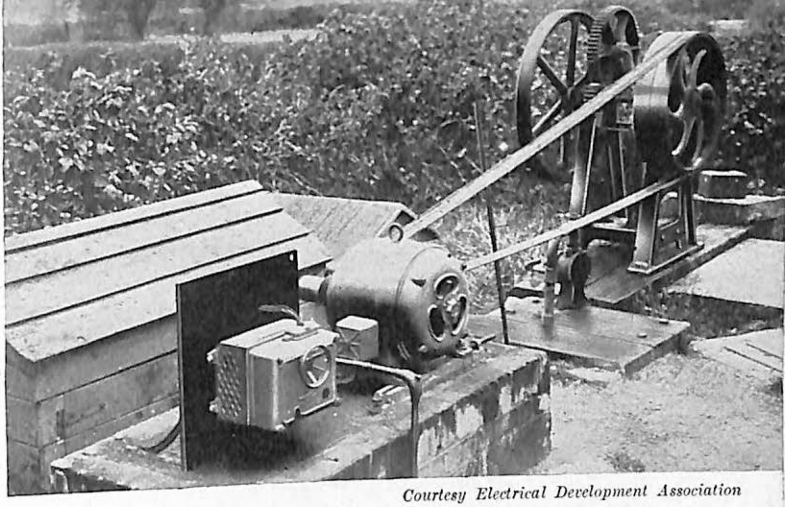


FIGURE 51. The movement of one turn of wire on the armature of a direct current electric motor.



Courtesy Electrical Development Association

FIGURE 52. An electric motor in use on a farm to drive a water pump. Can you see the starting handle which moves the slider of a rheostat ? By varying the resistance of the rheostat the motor current can be controlled.

Alternating current electric motors. The D.C. electric motor works as it does because of the attraction and repulsion between the magnetic fields of the armature and the field magnet. If a D.C. motor constructed with electro-magnets (not permanent magnets) is supplied with A.C., the two magnetic fields will continue to attract and repel each other as if D.C. were being supplied. The only difference is that, with a frequency of 50 cycles a second, there are two north poles repelling each other for one hundredth of a second, and then two south poles repelling each other for the next hundredth of a second. These motors can be called A.C./D.C. motors for they will work with either A.C. or D.C. They are very useful for small power outputs, such as for vacuum cleaners, fans, and shavers. The larger A.C. motors are not made in this way because they work on an entirely different principle.

An A.C. generator will act as an A.C. motor if in some way the rotor is spun at the right speed to be " in tune " with the A.C. supplied. Thus such a motor

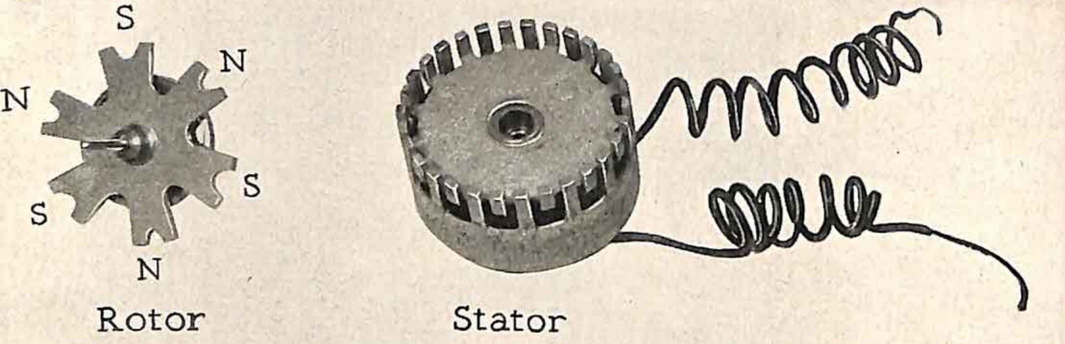


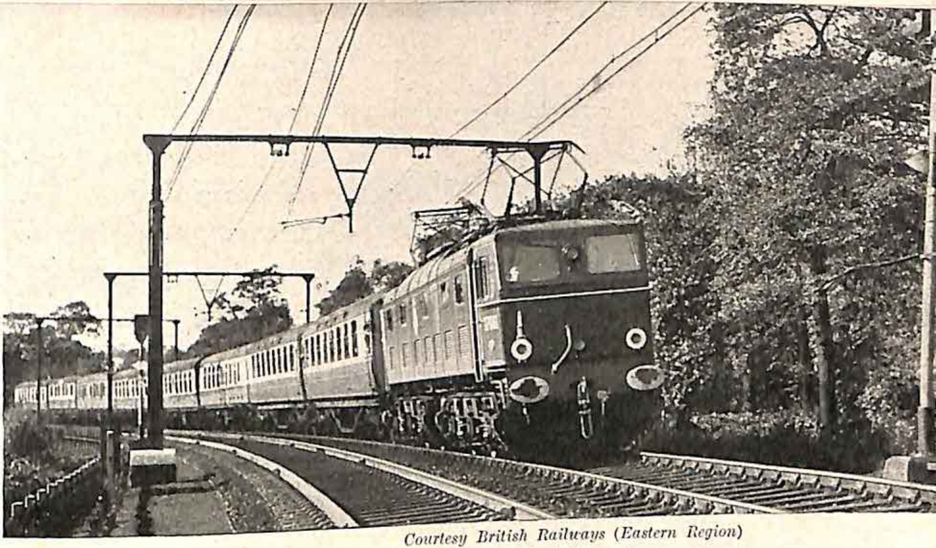
FIGURE 53. The rotor and stator of the synchronous motor of an electric clock.

can only revolve at one constant speed and this speed is determined by the frequency of the A.C. supply. This means that the rotor must always arrive in the right position to react correctly with the appropriate poles created by the alternations of the A.C. This is called a *synchronous* motor. If the frequency of the A.C. supply is kept constant these motors can be used through a system of gears to drive the hands of a clock.

PRACTICAL USE OF ELECTRIC MOTORS

Electric motors are used widely in the home and in commercial life. Machines for mixing food and sewing and washing, fans, cleaners, hair driers, shavers, clocks, and refrigerators use a variety of motors of many different powers and types.

The starter of a motor-car engine uses the D.C. supply of 6 or 12 volts from the batteries of the car. It is a small motor wound with a few turns of thick wire, and connected by thick wires to the battery and a robust switch. When this switch is closed, a very heavy current flows for a short time. This throws a small gear wheel into the cogs on the rim of the engine flywheel. The jerk which this gives to the flywheel spins it round to start the car.



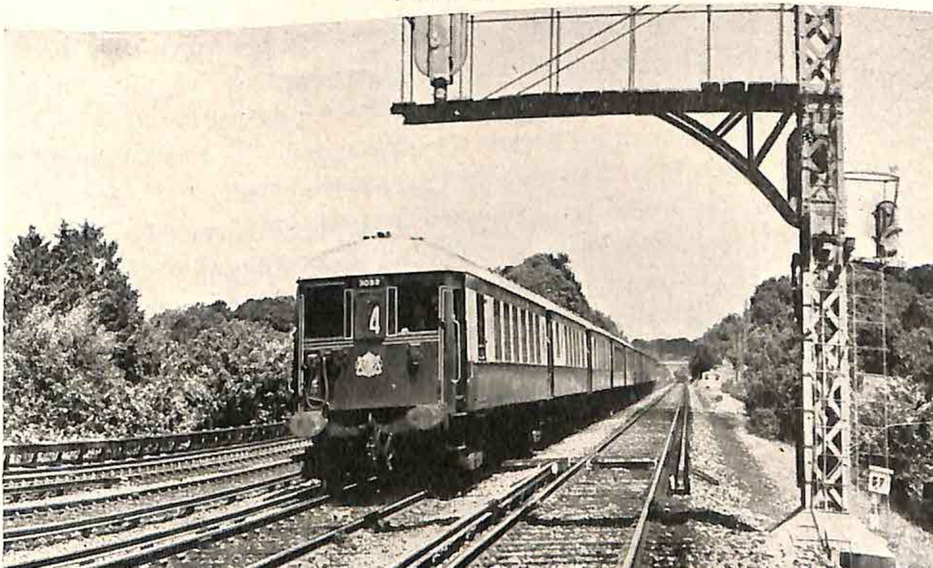
Courtesy British Railways (Eastern Region)

FIGURE 54. Manchester and Sheffield electric railway, showing overhead conductors.

Some electric locomotives, trolleys, and trams use large D.C. motors for their driving power. The current is supplied through overhead conductors, or through a "third" conductor rail by the side of one running rail. The electrical circuit is completed by using the running rails as the "return" wire. The motors are geared to the driving axles. The driver slowly and steadily allows more and more current to pass as the motors gather speed.

FIGURE 55. Southern electric railway, showing conductor rail. Notice how it changes from one side of the track to the other.

Courtesy British Railways (Southern Region)



To make a simple two-pole electric motor. (See Figure 56.) Cut 8 strips of tin-plate 1″ wide and 5″ long. Bind 4 of these together and bend them over a wooden block 3″ wide. Then solder the bent portions to form a solid armature. File the ends smooth and flat. Drill a $\frac{5}{32}$″ hole through its centre and solder this to a Meccano axle (Figure 56A).

Wind 100 turns of No. 32 S.W.G. enamelled copper wire on each half to form the coil of the armature. Bare the ends of the wire (56B).

Take two circular corks about $\frac{1}{2}$″ thick and make in them three holes. The centre hole is for the axle and the other two are for the bare wires (56C).

Mount and stick these to the axle to form the two segments of the commutator (56D).

Prepare the field magnet in exactly the same way and leave 6″ of free wire at both ends. Fix the field magnet to a wooden base, with a piece of tin-plate below the hole to act as a bearing (56E).

Build a support of Meccano strips for the top bearing of the axle. Screw this to the base board with the axle in position so that the armature turns freely. Judge the axle length correctly so that the poles move near one another (56F).

Mount a cork on one of the Meccano upright strips. Slit the sides of the cork with a penknife and insert two long copper wires that will act as brushes for the segments of the commutator (56G).

Connect in series the armature, the field magnet, a switch, a rheostat, and a battery (56H).

Spin the armature to start the motor and adjust the copper brushes to " make " and " break " the electric current at the right moments. When are the right moments ? Will it drive a small light fan ?

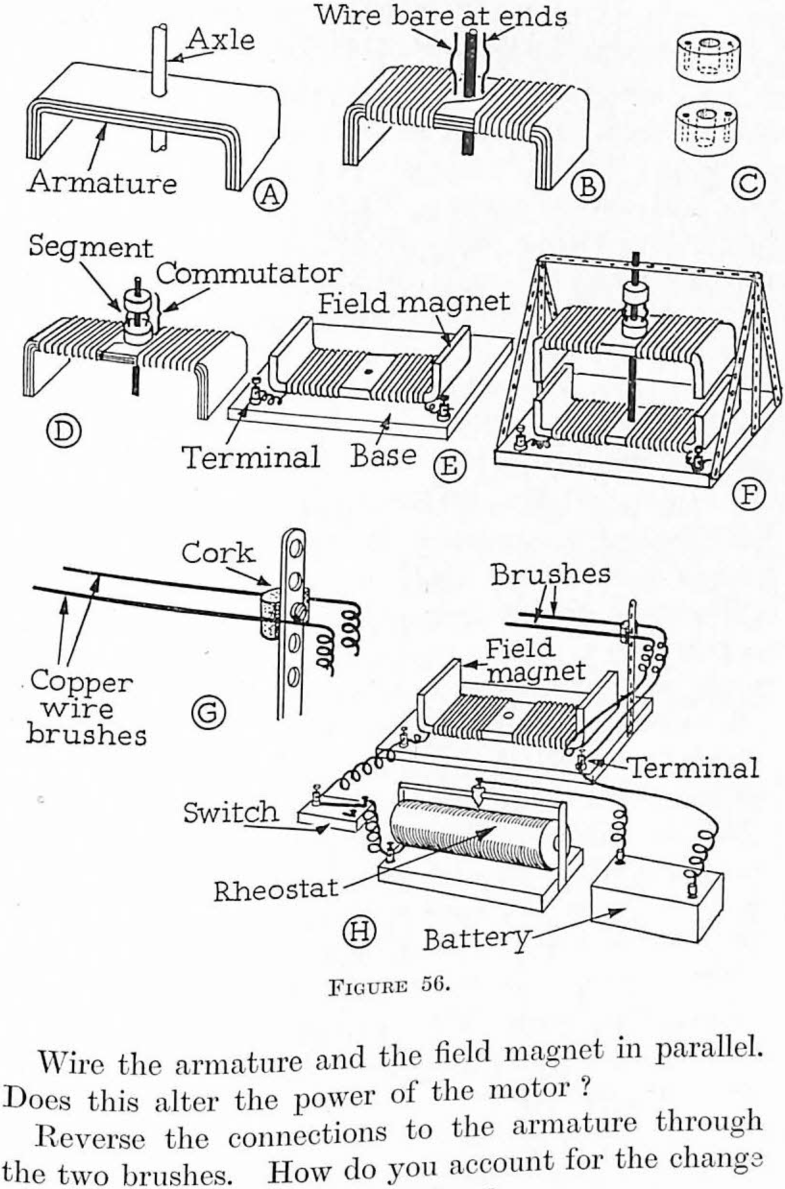


FIGURE 56.

Wire the armature and the field magnet in parallel. Does this alter the power of the motor ?

Reverse the connections to the armature through the two brushes. How do you account for the change which you notice in the rotation ?

How can an " intermediate " switch be connected to reverse the direction of rotation of the motor ?

Problem C: **WHAT IS ELECTRO-MAGNETIC INDUCTION?**

It is reasonable to ask why A.C. is supplied to homes and factories when D.C. is more suitable for many purposes. D.C. is the ideal current for radios, motor-cars, and electric traction. A.C., unlike D.C., cannot be used to charge an accumulator. A.C. cannot be used for electro-plating. In fact, the mains A.C. has to be changed to D.C. for use in radios and for some electric railways.

The answer is that the pressure of A.C. can be changed easily from one value to another. The device which does this transformation is called a *transformer*, and it uses the principle of electro-magnetic induction.

A generating station producing sufficient power to supply a large city could send its electrical energy there at a suitable low pressure through thick and massive bars made of a good conductor. But this would be an expensive and inconvenient method. An alternative method, however, is to supply the same power by a relatively small current at a relatively high pressure. It is cheaper to send a small current because only thin wires are needed. It is extremely useful to be able to transmit a small current at a very high pressure and to be able to change it wherever we need it into a large current at a low pressure.

High pressures of 132,000 volts are used on the overhead *transmission lines* of the "Grid" system in Britain. As more and more electrical power is needed in the future, it will become necessary to transmit this at 380,000 volts. Most consumers of the electricity of this "Grid" system use appliances requiring a supply at pressures that lie between 2 volts and 500 volts.

Question 1. **How does an Induction Coil work ?**

The experiments described in Problem B, Question 2, show that the value of an induced electro-motive force (E.M.F.), produced in a solenoid by the movement of a permanent magnet, depends upon:

(*a*) the strength of the magnet,
(*b*) the number of turns of wire in the solenoid,
(*c*) the speed with which the magnet is inserted into the solenoid.

This can be summarized by saying that *the induced E.M.F. depends on the rate of change of the magnetic lines of force* passing through the solenoid.

We learnt also that the direction of the induced E.M.F. depends on two things:

(*a*) the kind of pole (N or S) that is moved relative to the turns of the solenoid and along its axis,
(*b*) whether the pole is moved into the solenoid or withdrawn from the solenoid.

A North pole inserted in a solenoid gives an induced current in the same direction as a South pole withdrawn from the same solenoid.

An E.M.F. will be induced in the solenoid even if it is not connected to a complete circuit. If the solenoid is connected by conductors to form a circuit then a current will flow.

The induction coil. This is a device which produces a high induced E.M.F. Just the same principles of induction will apply to produce a high induced E.M.F. however the magnetic field is created in the solenoid. For instance, instead of inserting a magnet into the solenoid, it is possible to place an electro-magnet inside the solenoid and then to switch the current

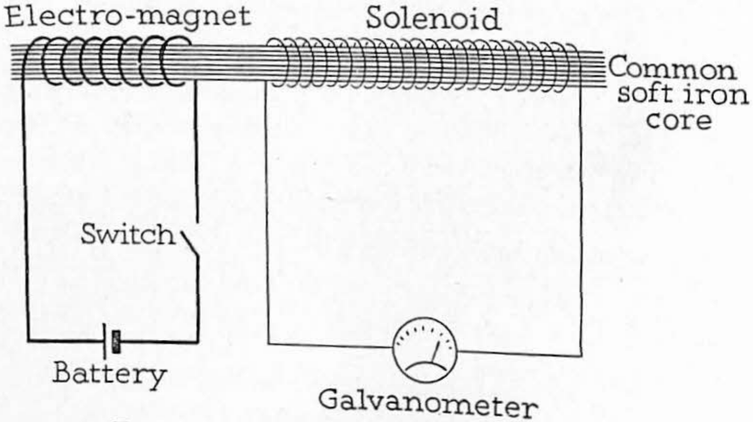


FIGURE 57. The principle of the induction coil.

on and off. This gives the same effect as inserting and withdrawing the magnet.

The induction coil uses this method and produces a considerable E.M.F. because

(*a*) the electro-magnet can be made much stronger than a permanent magnet,

(*b*) the current can be switched on more rapidly than a magnet can be inserted into the solenoid,

(*c*) the electro-magnet and the solenoid can be built together on the same soft iron core to ensure close contact between them. In this way no change in the magnetic lines of force can escape. It is even possible to wind the solenoid outside and on top of the electro-magnet.

The essential parts of an induction coil are shown in Figure 58. The solenoid of the electro-magnet is called the *primary coil*: it is usually composed of a few turns of thick insulated copper wire. Surrounding this is the *secondary coil*, a large solenoid of thousands of turns of thin insulated copper wire leading to two high-pressure terminals. As in the electric bell a " make "

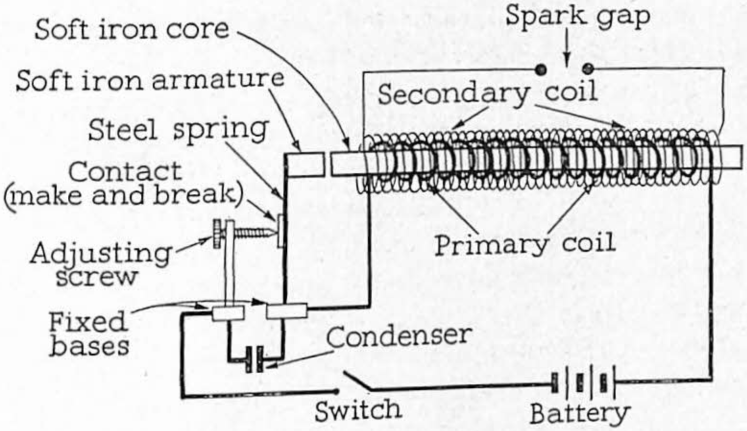


FIGURE 58. The essential parts of an induction coil.

and " break " is inserted in the primary circuit. This automatically operates many times every second.

When the circuit is closed at " make " the current grows in the primary coil, inducing an E.M.F. in one direction in the secondary coil. This growth of current takes a small but definite time. At " break " the current ceases to flow very rapidly, much more rapidly in fact than it grows at " make." One reason for this

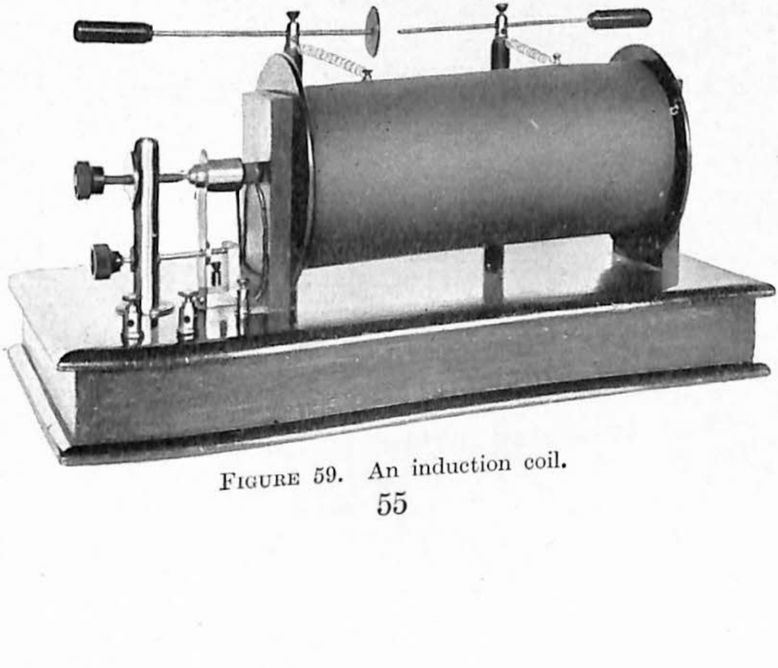


FIGURE 59. An induction coil.

is that a condenser is inserted (see Figure 58) and used in such a way that sparking is minimized, thus allowing the current to cease abruptly. In this way the induced E.M.F. at " break " is very much greater than it is at " make." The whole cycle of " make," " on," " break," and " off " takes place quickly—perhaps fifty times a second.

Induction coils have many applications. They are used to supply the spark for the engines of motor-cars, to produce X-rays, and to assist in modern atomic research and in medicine.

Let us now consider two of the practical uses of the induction coil.

Car ignition system. Advantage is taken of the large E.M.F. at " break " to produce a spark just at the right moment to fire the explosive mixture in the cylinder. A spark requires only a very small current. The precise moment of firing is determined by a cam, connected directly to main axle of the engine. The cam opens a contact which breaks the primary circuit. As the engine turns, each sparking plug in turn, one after the other, is connected to the secondary coil of

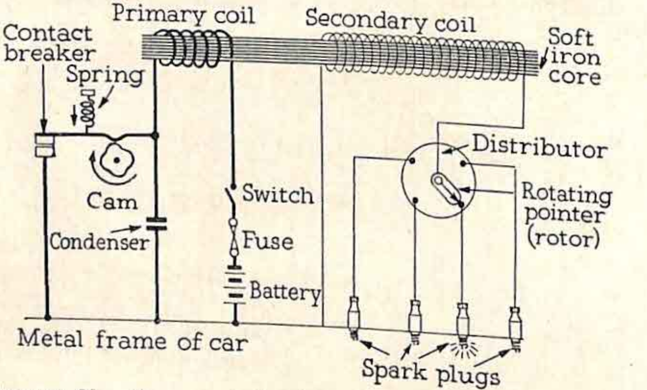


FIGURE 60. How an induction coil is used in the ignition system of a motor-car.

an induction coil. The rotating metal pointer of the *distributor* chooses the lead to the correct sparking plug.

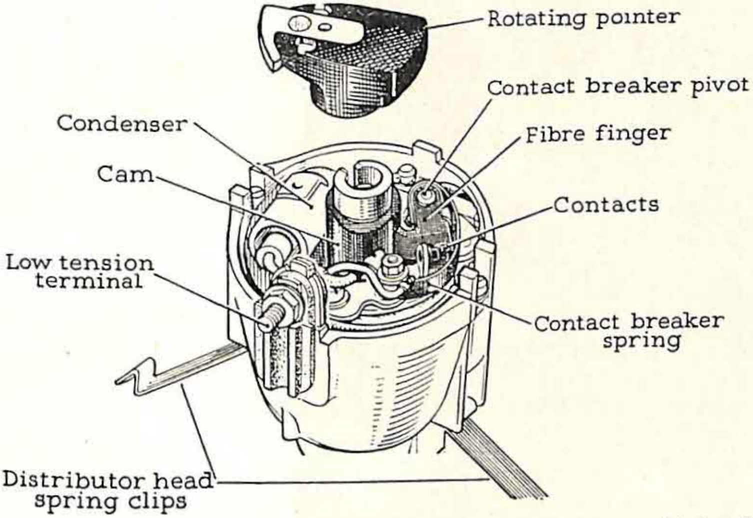
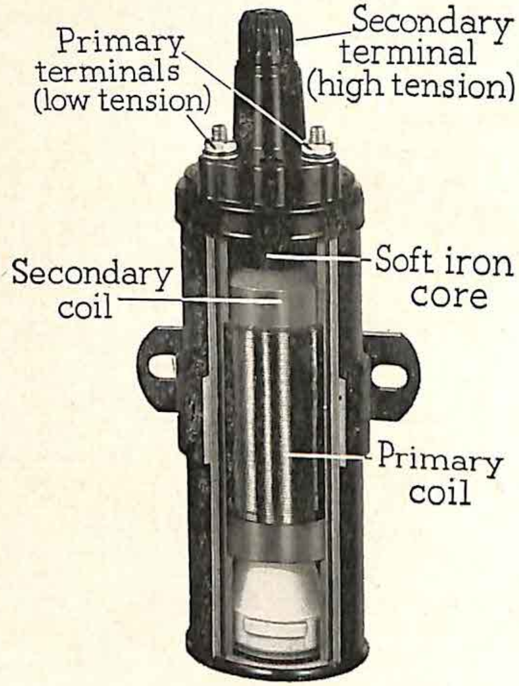


FIGURE 61. Motor-car contact breaker and distributor with head removed. The rotating pointer fits on the top of the cam and comes opposite terminals in the distributor head.

Examine the ignition system of a car. Take off the distributor head. Turn the engine slowly by hand. Watch the contacts " making " and " breaking." Stop precisely when a " break " occurs. Does this happen when the rotating metal pointer faces a contact to a lead ? What is the order of firing the plugs ? Can you see how the condenser is connected ? How are the contact points adjusted and how far apart should they be at " break " ? Take out the particular sparking plug which should fire at this position of the distributor. With care insert the blunt end of a pencil in the hole in the cylinder head. Can you feel the top of the piston ? Why must you take care not to drop anything in the hole ?


Primary terminals (low tension)
Secondary terminal (high tension)
Secondary coil
Soft iron core
Primary coil

Courtesy J. Lucas & Co., Ltd.

FIGURE 62. Cut section of car ignition coil.

Find the ignition coil. Look for the two terminals of its primary coil. Notice where the wires connected to these terminals lead. Compare this with the wiring diagram of Figure 60. Trace the secondary coil wire to the distributor and from there to the plugs. Unscrew the insulated cap holding this wire to the ignition coil. Examine the wire and its insulation. Why is there a thick coating of rubber? Why have the primary coil wires no such thick insulation?

Electric cattle fence. We have seen how an induction coil can supply a sudden and very large E.M.F. in the secondary circuit of a car ignition system. This same idea of a sudden and large E.M.F. is used to electrify a cattle fence in order to keep the cattle within bounds.

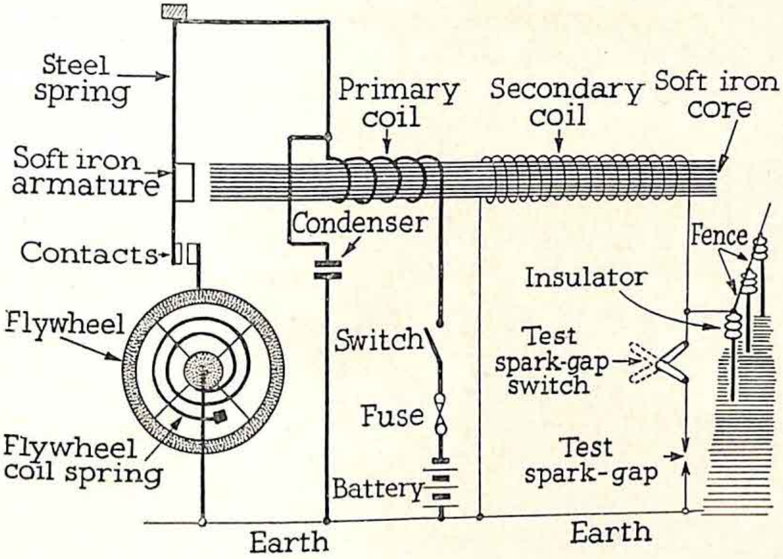


FIGURE 63. How an induction coil is used to provide the high tension on an electric cattle fence.

You will be able to follow the wiring diagram of the circuits by examining Figure 63. Compare this with the car ignition system diagram. Where the car employs a revolving cam to provide the " make " and " break " device, the cattle fence simply uses a spring-loaded flywheel. Every time the spring of the flywheel uncoils—the two contacts are pressed together, the primary circuit is completed, the iron core is magnetized, the armature is attracted, the flywheel is spun round, the flywheel spring is wound up again, the primary circuit is broken, and a strong impulse of E.M.F. is produced in the secondary circuit. As soon as the flywheel completes its spin and comes back again, the whole cycle of operations is repeated. This continues as long as the switch in the primary circuit is closed.

The *high tension* (H.T.) impulse, as it is called, is led to a long wire fence mounted on insulators around the

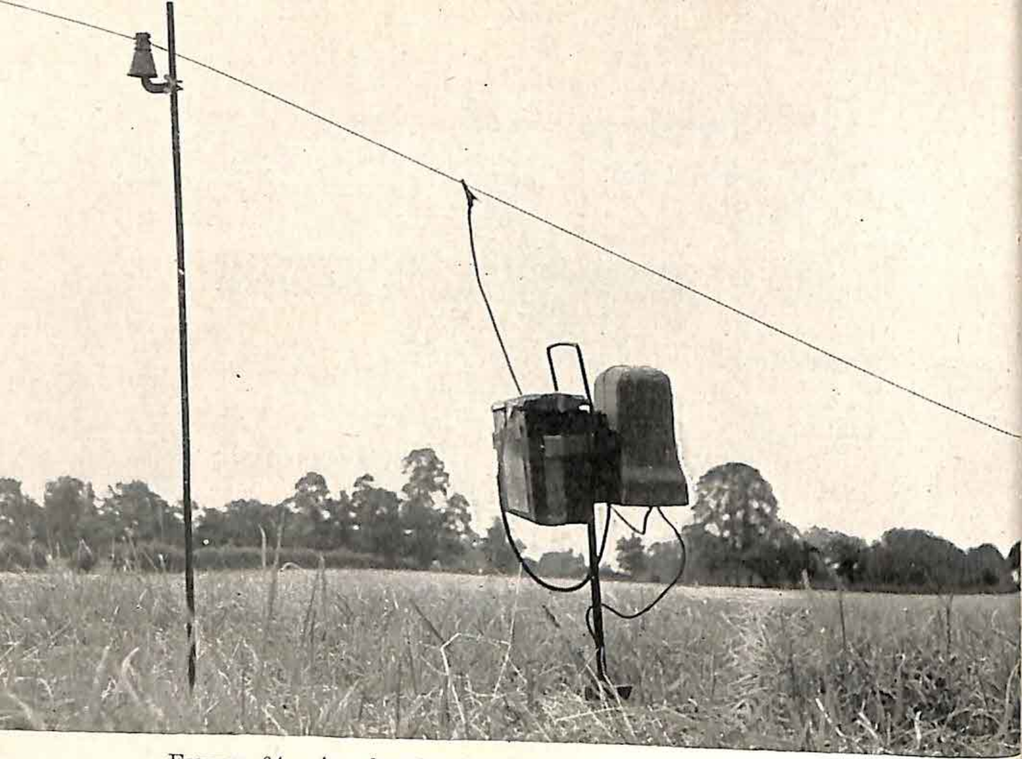


FIGURE 64. An electric cattle fence showing the insulated fence wire, the spike into the ground (earth connection), the battery, and the induction coil box.

field. The return " wire " is the earth and the circuit is only completed if some animal standing on the earth touches the wire fence. The H.T. impulse does not kill the animal but gives it a shock so that it learns to keep away from the fence in future.

SOMETHING YOU MAY CARE TO DO

Make an electric cattle fence. This can be done by several of you working together. Plan carefully how you can build this apparatus, assemble all the components, then start with a strong wooden base to which everything can be firmly secured.

You will want an induction coil which has a soft iron core that attracts an armature on a spring. Mount a large heavy flywheel on an axle and bearing. Attach projections to the armature of the induction coil and to the circumference of the flywheel. Fasten contact points of a car ignition system to these projections, so that they touch one another as the flywheel spins back and forth. Instead of the coiled spring shown in Figure 63, the weight of the projection on the flywheel can be used to return it to the " make " position. You will have to put a screw to act as a " stop " to prevent the flywheel rotating too far. You may want a second stop to prevent the armature being knocked too far back at " make." You will see by examining Figure 63 how to connect up the condenser, the test spark-gap and its switch. The photograph in Figure 65 shows how to assemble these components.

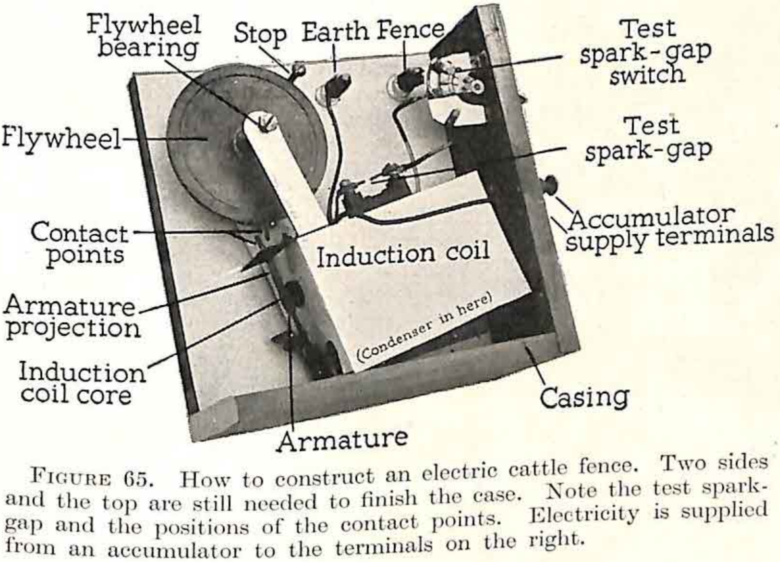


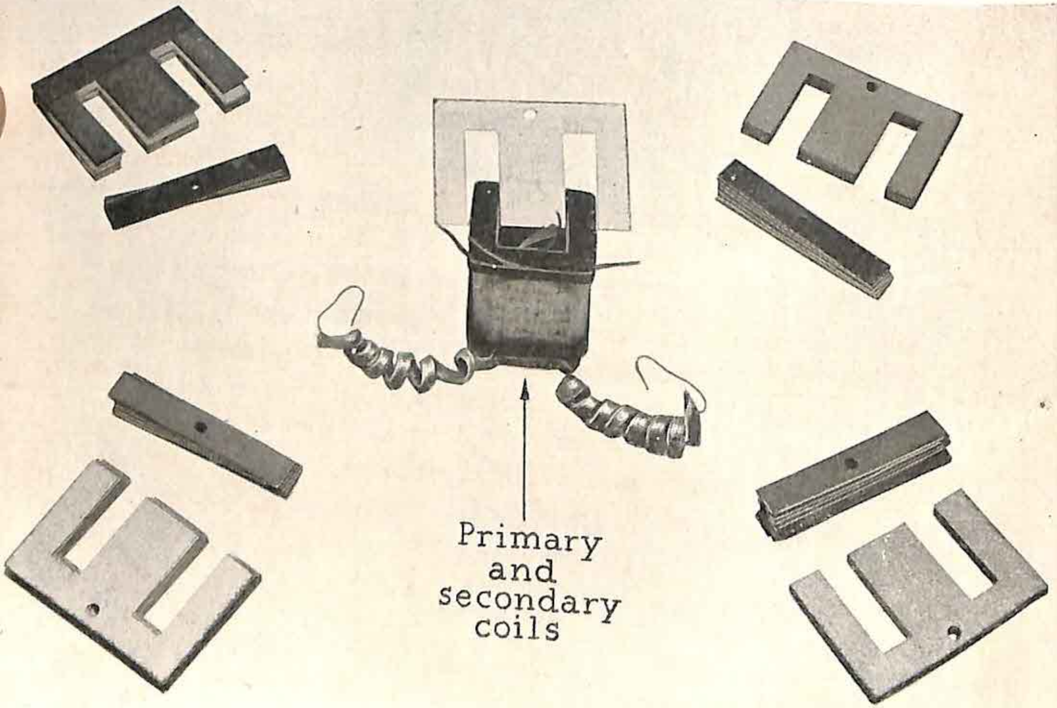
FIGURE 65. How to construct an electric cattle fence. Two sides and the top are still needed to finish the case. Note the test spark-gap and the positions of the contact points. Electricity is supplied from an accumulator to the terminals on the right.

Question 2. **How is a Transformer Built ?**

Faraday's famous experiment with the two solenoids wound on a soft iron ring (see Figure 23) was the first demonstration of electro-magnetic induction. He had built a transformer although he did not give it this name.

The primary and secondary coils on the soft iron core of an induction coil can be regarded as a transformer. The only real difference between the induction coil and the transformer is that the " make " and " break " mechanism is omitted in the transformer. Instead of supplying a current which starts and stops in the primary coil, an alternating current—which rises, falls, and reverses—is used.

FIGURE 66. A small transformer for use in a radio. Note the E and I stampings for the core have been separated and laid aside. The primary and secondary coils are wound together and fit on the middle arm of the E stamping.



A transformer, then, converts alternating current electricity from one pressure to another. It consists of a core made of soft iron stampings. Various patterns are used, a U and T shape, and an E and I shape being common. These stampings are put together first one way and then the other around and through the primary and secondary coils. The secondary coil is wound on, and carefully insulated from, the primary coil.

The change in pressure depends on the relative number of turns of wire in the two coils. The ratio of the pressure supplied in the primary coil to the pressure induced in the secondary coil is, apart from small losses, the same as the ratio of the number of turns of wire in their respective coils. This can be written in an equation :

$$\frac{\textbf{Pressure in primary coil}}{\textbf{Pressure in secondary coil}} = \frac{\textbf{Number of turns in primary coil}}{\textbf{Number of turns in secondary coil}}$$

Therefore it follows that if the secondary coil has more turns than the primary coil, the transformer is called a "*step-up*" transformer, because the pressure from the secondary coil is raised. If the secondary coil has less turns than the primary coil, it is a "*step-down*" transformer.

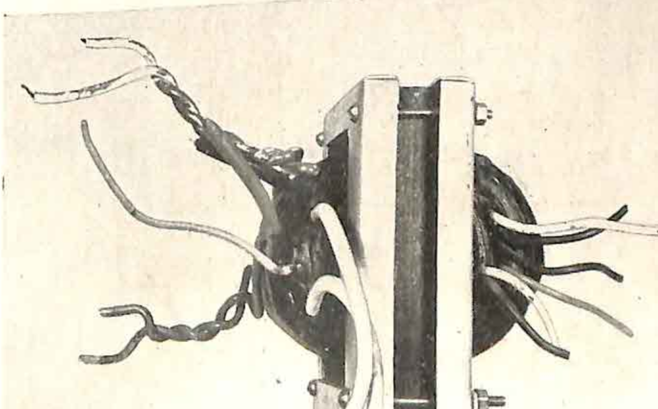


FIGURE 67. A mains supply transformer with several separate secondary coils. This is both a "step-up" and "step-down" transformer producing a large number of different pressures for a radio.

Modern transformers are so well-made that there is (*a*) little loss of the alternating magnetic field outside the primary and secondary coils, (*b*) little difficulty in alternating rapidly the direction of flow of magnetic lines of force in the iron of the core. Thus there is hardly any loss of energy in a transformer. Electrical energy going into the primary coil is given out again in the secondary coil. If we assume no loss of energy at all, then the energy supplied equals the energy delivered. This can be written:

Energy input = Energy output

If we remember that Energy = Power × Time, then this equation can be rewritten as:

Power input = Power output

or $$\textbf{Pressure} \times \textbf{Current in primary coil} = \textbf{Pressure} \times \textbf{Current in secondary coil}$$

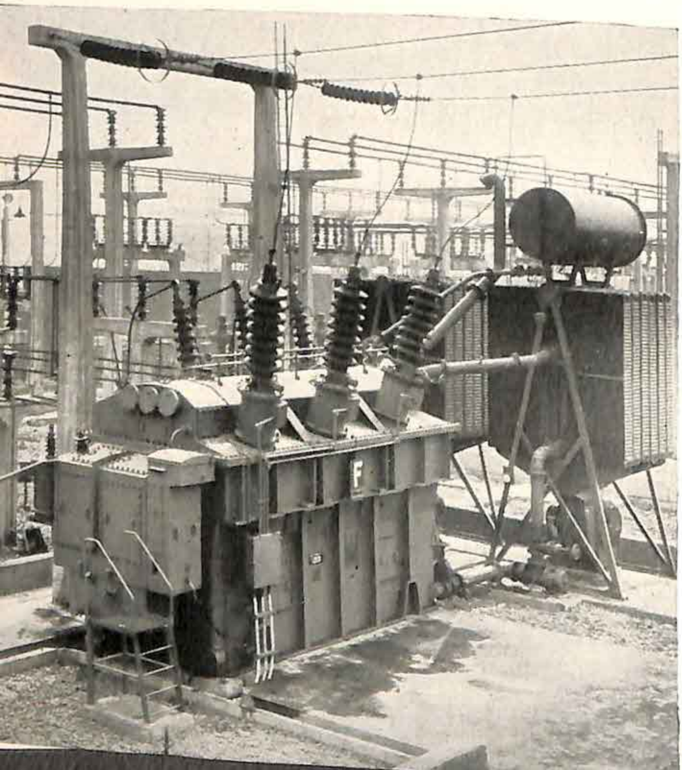


FIGURE 68. A large modern three-phase transformer. The energy lost in the transformer is dissipated as heat in the large radiators at the side. Oil circulates through the transformers and radiators. Surplus oil is stored in the cylindrical container.

Courtesy Ferranti, Ltd.

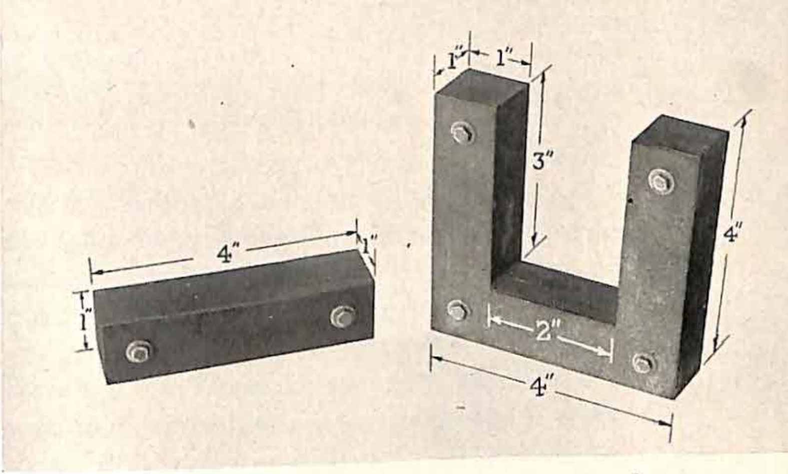


FIGURE 69. How to build the soft iron core of a transformer.

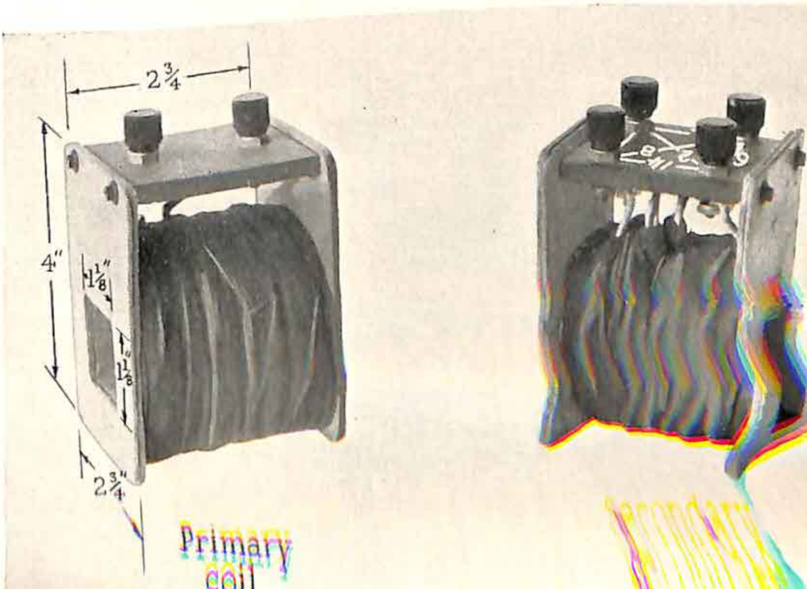
SOMETHING YOU MAY CARE TO DO

Build a "step-down" transformer for use on the mains supply of alternating current.

Cut out 60 sheets of soft iron to form U shape and I shape "stampings" as in Figure 69. These are easier to cut than the E and I shape stampings shown in Figure 66. Old tin cans will do well for this purpose. Flatten each one, bolt them together to form the core. File the edges flat.

Make cardboard formers to fit over the two arms of the U core as in Figure 70. Wind 1680 turns of No. 26

FIGURE 70. How to wind the coils of a transformer.



S.W.G. D.C.C. copper wire on one "former." This is the primary coil and has 7 turns per volt when used on a 240-volt A.C. mains supply.

On the other former wind 98 turns of No. 16 S.W.G. D.C.C. copper wire. This is the secondary coil. After 14 turns take off a tapping to one terminal, and after a further 28 turns take off another tapping to a second terminal. The two ends are connected to terminals.

Assuming that the U and I fit together neatly to form a complete core, there will be in the secondary coil, apart from small losses, 1 volt for every 7 turns. This secondary coil will therefore give 6 different A.C. pressures as shown in Figure 71.

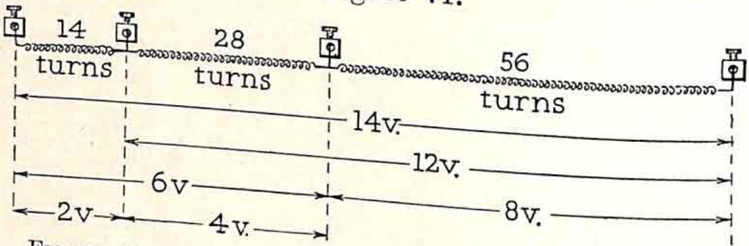


FIGURE 71. How six different pressures can be obtained from a single secondary coil.

Build a wooden clamp to hold the core together and mount the coils as shown in Figure 72. You have then built a mains supply "step-down" transformer which you can use for many purposes.

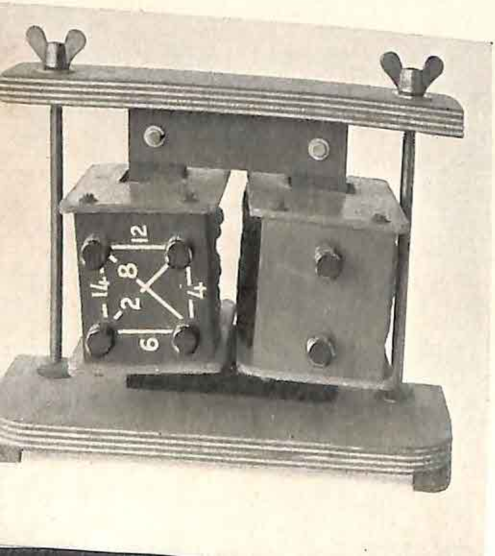


FIGURE 72. How to assemble the core and the coils of a transformer. The clamp should be screwed down firmly.

Question 3. **What are the Uses of a Transformer ?**

In many places electricity is supplied to homes and factories at 240 volts A.C. This pressure can be used satisfactorily for many appliances—lamps, fires, cookers, and motors. However, for some other pieces of equipment it is necessary to have lower pressures. For instance, most electric bells for use in houses require 3, 5, or 8 volts. This has been chosen because the circuit wires can have thinner, and therefore cheaper, insulation, and also because the pressure is not dangerous if a wet hand should accidentally touch a faulty bell push outside a door. We learnt in the last Question how to construct a " step-down " transformer which could be used in a house bell-circuit.

Some small power electric motors in sewing machines and shavers also need " step-down " transformers.

A radio set needs pressures suitable for many purposes—to supply the filaments of its valves, to light the pilot lamps, and to provide the high tension supply for the valves. Hence a multi-purpose transformer, often combining " step-up " and " step-down " secondary coils, is constructed. Look at Figure 67.

In some makes of cinema projector a " step down " transformer is built into the base to supply a large current at a low pressure for the filament of the lamp. This is because a thick filament burning at a low pressure is more stable and stronger than the finer longer filaments necessary in lamps using 240 volts.

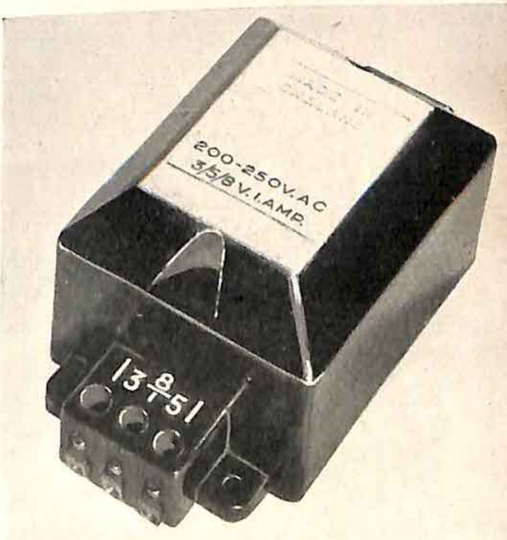


FIGURE 73. A bell transformer.

SOME THINGS YOU MAY CARE TO DO

1. Construct another primary coil of 750 turns of No. 20 S.W.G. D.C.C. copper wire. This primary coil has fewer turns of wire than the first primary coil you built (see Figure 70): it will therefore carry a larger current. It will, however, get hot after a short time and thus it must only be used for a few seconds at a time.

2. Construct a secondary coil by winding five turns of thick copper rod of No. 6 S.W.G. round another cardboard "former." Screw on to the ends of this rod two large terminals. (See Figure 74.)

3. Cut out a ring from some thick copper sheet and beat this into a shallow circular trough. Attach a wooden handle to the trough. (See Figure 75.)

4. Build a transformer of this primary coil of 750 turns, the five-turn secondary coil, and the soft iron core. Tighten two thick iron nails to the terminals of the secondary coil so that their points just overlap and touch each other. Switch on the 240-volt A.C. to the primary coil. You will notice that so much heat is generated at the points of the nails that they become red hot and even melt. If you switch off at the right moment the two nails will be welded together. This is the process of *electric welding*.

FIGURE 74. A secondary coil of five turns of thick copper rod.

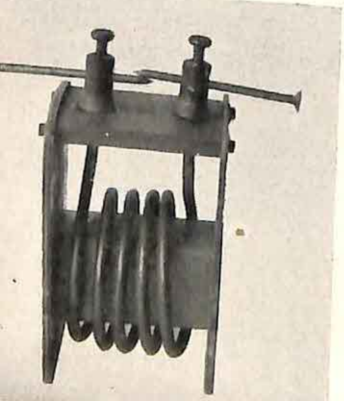
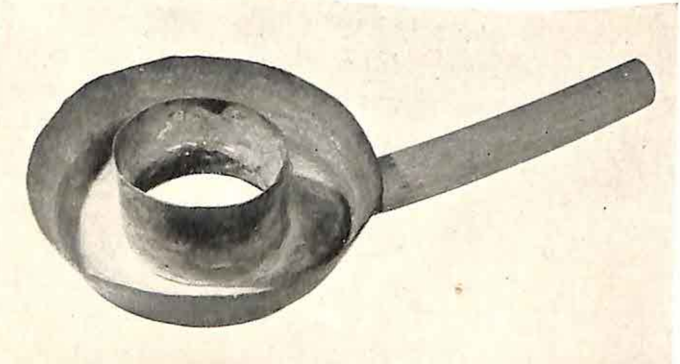


FIGURE 75. A one-turn secondary coil beaten into the shape of a trough.



5. With the same circuit as described in the previous paragraph join the terminals of the five-turn secondary coil to about 2 feet of thick iron wire. Switch on the primary coil. Notice how the wire gets warm quickly. In the same way low pressure hot-plates become hot and frozen water-pipes can be thawed by the passage of large currents of electricity.

6. Use the same primary coil again but this time use the one-turn circular trough as the secondary coil in the transformer. A large current will flow through the one-turn secondary coil and much heat will be generated. In the channel section of the trough put some solder. Notice how quickly this melts. This is the principle of the *electric induction furnace,* which is used for making special steels.

Problem C : What is Electro-magnetic Induction ?

Question 4. **How is Electric Power Transmitted ?**

We have examined in the last Question examples of the heating effects due to large currents produced by "step-down" transformers. We purposely designed these circuits to produce the heat.

On the other hand, if we wish to transmit a large amount of electric power over a considerable distance we do not want to waste any electricity in the form of heat in the conducting wires from the generating station. Therefore we must design our transformers to deliver small currents. Let us look again at the power equation for a transformer.

Power input to primary coil =
Power output from secondary coil

or

Low pressure × Large current in primary coil
= High pressure × Small current in secondary coil

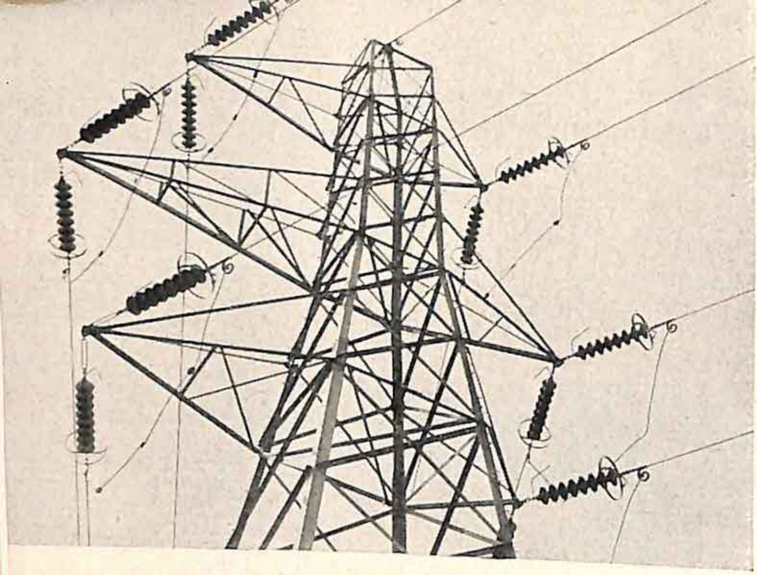
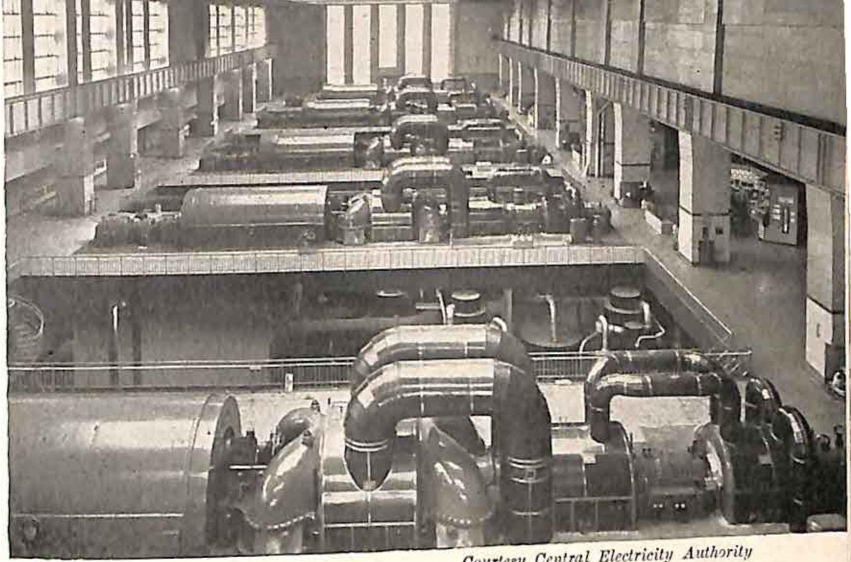


FIGURE 76. High tension 132,000 volt transmission lines supported by long porcelain insulators.

So, in order to have small currents in the conducting wires, called *transmission lines*, the pressure for a given power must be high. Consequently we must use a " step-up " transformer.

Another advantage in transmitting electric power at small current values is that only thin conductors are required. This saves the large cost of thick heavy wires and the construction of massive pylons to carry these wires. There is, however, a disadvantage : the high pressures used need long insulators to prevent a leakage of the electricity over their surfaces to earth. This can be overcome by the use of insulators in the form of inverted cups. Why is this shape desirable ?

Generation and transmission system of electricity. We have learnt that less energy is lost in transmitting electricity over considerable distances if the electricity is first converted by transformers to a high pressure. The electricity must be changed back again after transmission to a low pressure so that it can be used with safety. Engineers refer to the terms *high tension* (H.T.) and *low tension* (L.T.) when speaking of these pressures.



Courtesy Central Electricity Authority

FIGURE 77. Interior of a large modern power station. Note that the three turbines on the right are coupled directly to the A.C. generator. Why are there three turbines driving each generator ?

Large generators of electricity for the supply mains are not simple alternators. They are the same as three alternators in one machine, and they produce what is called *three-phase alternating current.* (See Figure 68.) Three wires and a " neutral " wire are needed to carry this supply. Three-phase generators can be constructed to produce more power, and three-phase motors can be more easily controlled, than the simple alternating current machines we have described earlier in this Unit.

It becomes convenient when there are many sources of supply of electricity to connect all the power stations together in one common national system. In this way the generating plant available is pooled and the varying demands for electricity in different areas is supplied more economically. Those areas with a surplus of power are able to assist those where there is a shortage.

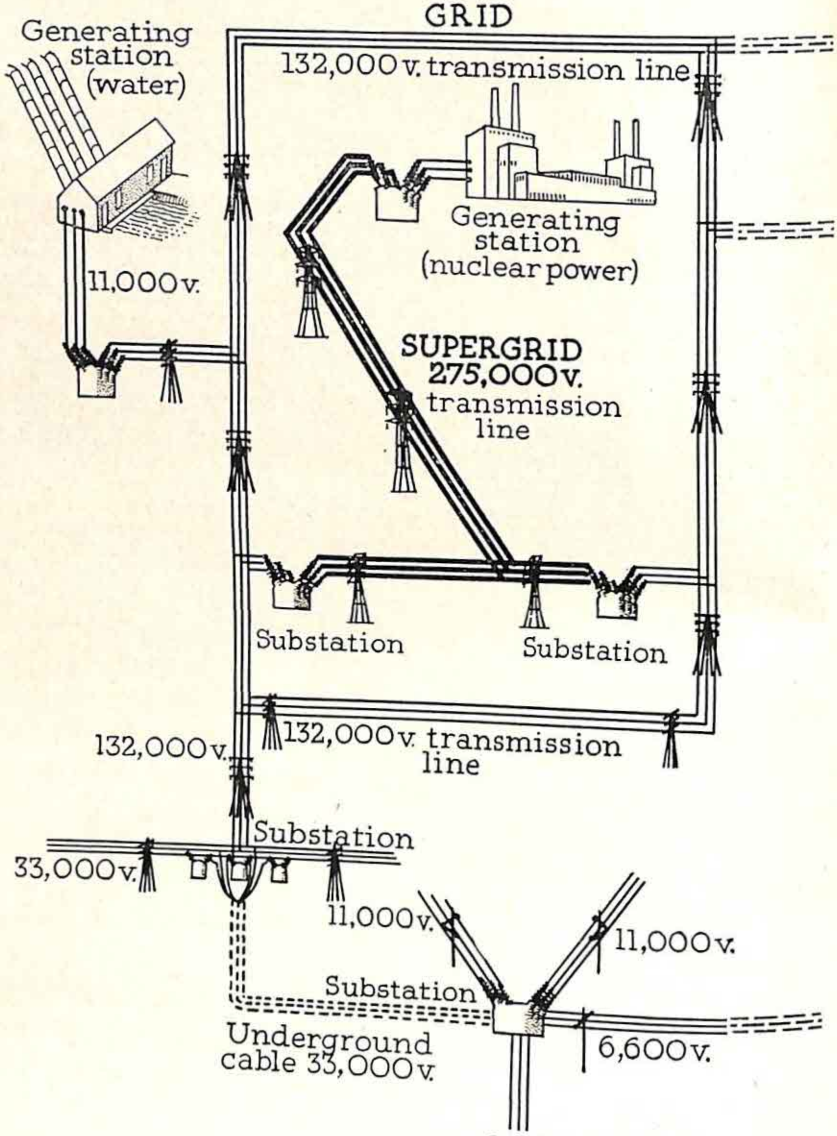
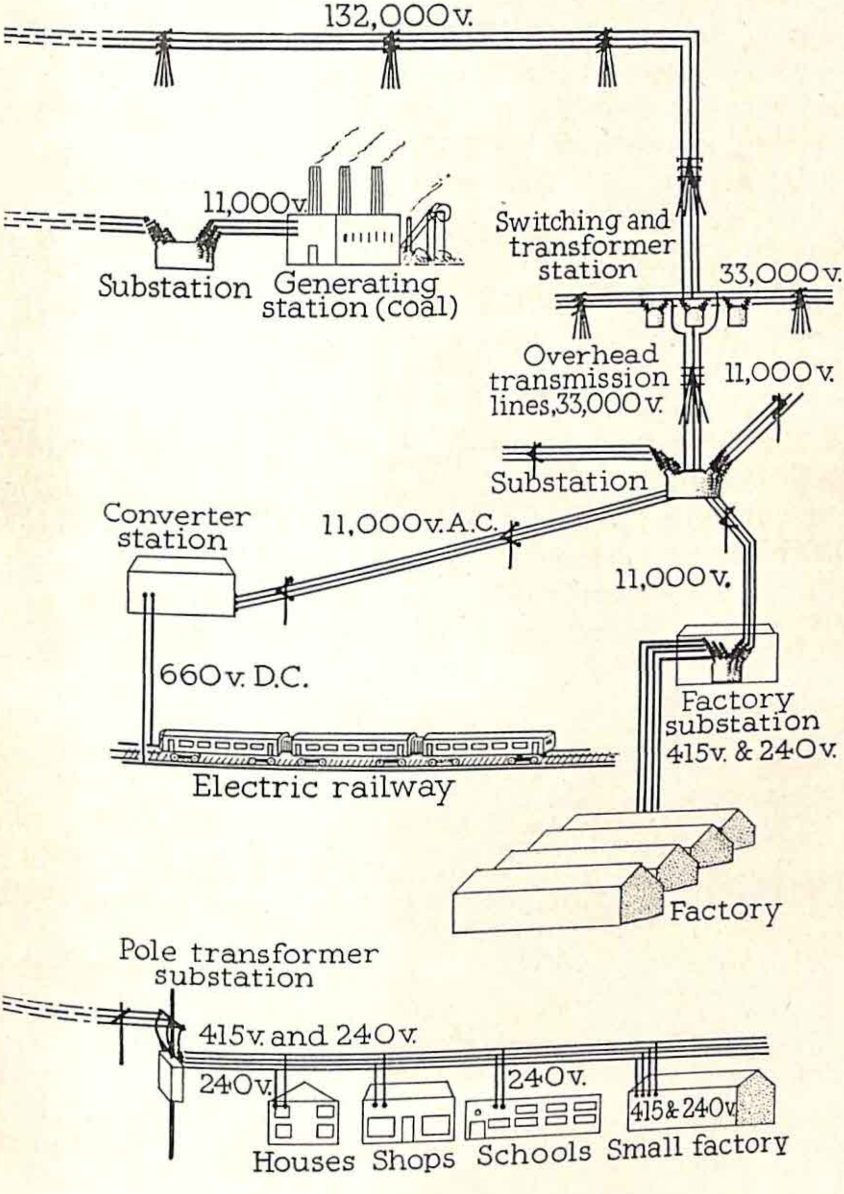

GRID
Generating station (water)
132,000 v. transmission line
Generating station (nuclear power)
11,000 v.
SUPERGRID 275,000 v. transmission line
Substation
Substation
132,000 v.
132,000 v. transmission line
Substation
33,000 v.
11,000 v.
11,000 v.
Substation
Underground cable 33,000 v.
6,600 v.
6,600 v.

Figure 78. Generation, transmission and distribution of electricity.

This system consists of a complicated network of H.T. transmission lines which are fed, joined, and



tapped through switching and transforming stations at convenient places.

These transforming stations "step-up" or "step-down" the pressure; they are often called *sub-stations*. There may be many generating stations all supplying electricity to the common system, some contributing more at one time than another according to their efficiency or availability.

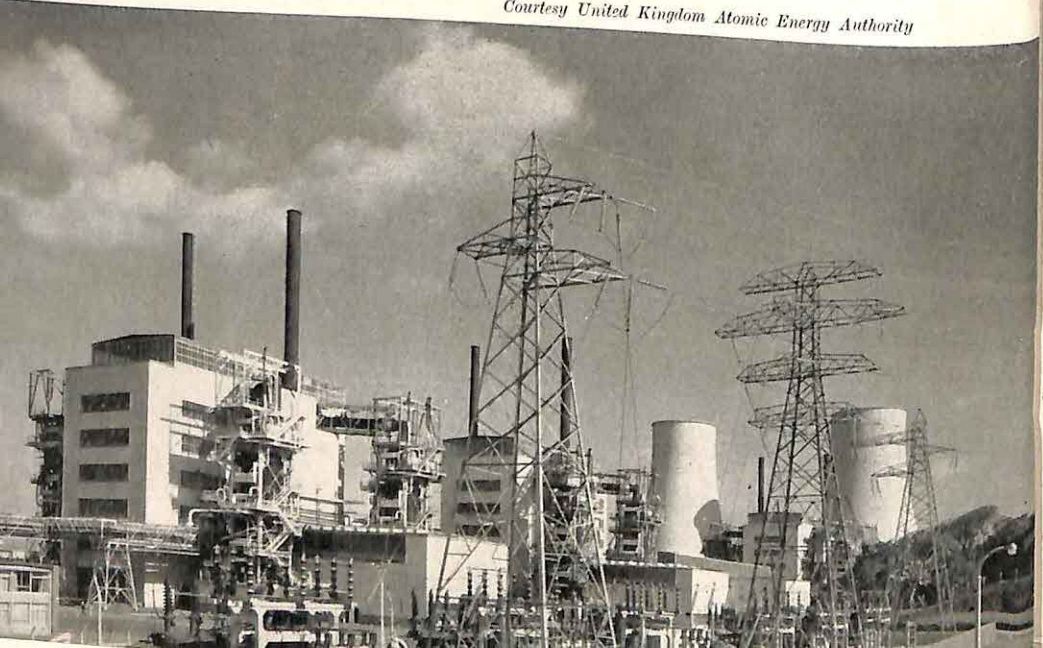
Look at Figure 78 which shows in a simplified way how the generation, transmission, and distribution of electricity take place in Britain.

Two generating stations are shown, each producing A.C. at 11,000 volts. They feed the common system through sub-stations which "step up" the pressure to 132,000 volts. The common system or circuit is called the *Grid*.

A third generating station is shown in Figure 78, at which the pressure is "stepped-up" to 275,000 volts to form a *Supergrid*. This Supergrid system is connected where necessary to boost the 132,000 volts Grid system through "step-down" transformer sub-stations.

FIGURE 79. Calder Hall, Cumberland, the first large-scale nuclear power station in the world. The turbine halls are between the reactor buildings and the cooling towers are in the distance. The electrical sub-station is in the foreground.

Courtesy United Kingdom Atomic Energy Authority



Because the real network, as shown in Figure 80, is complicated there must be central control rooms. The control engineers are informed where the electricity comes from and where it goes to. Thus they can tell the engineers in the various power stations when to shut down and when to start up their generators.

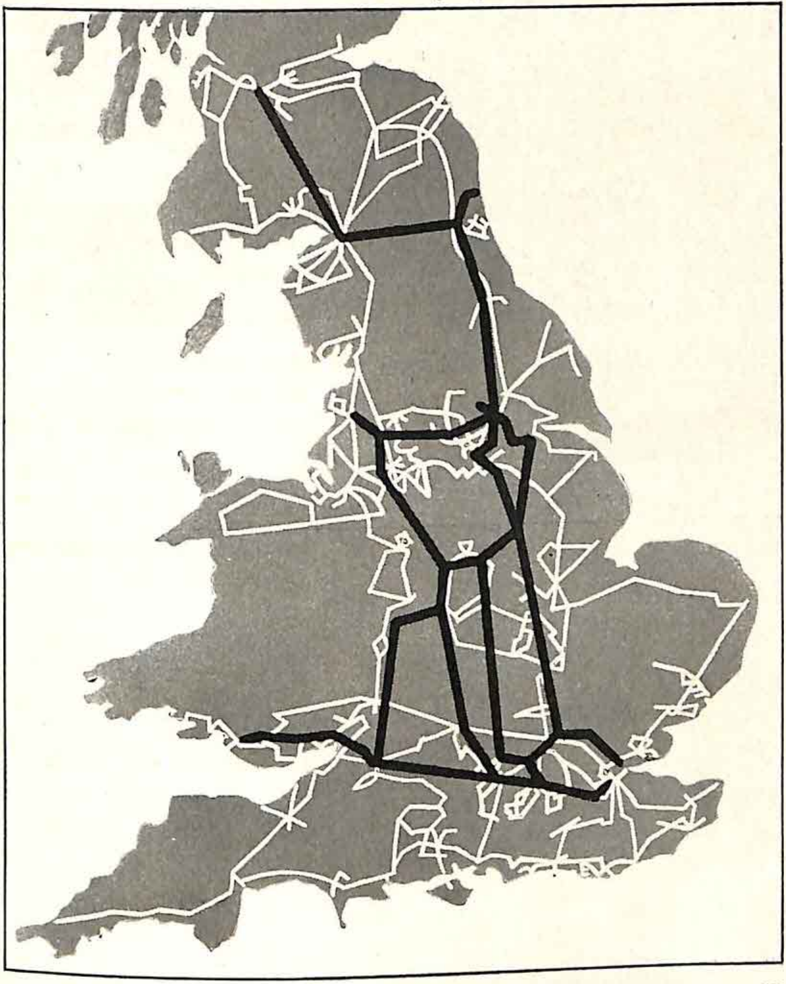


FIGURE 80. The network in Britain of the 275,000 volts Supergrid (shown in black) and the 132,000 volts Grid (shown in white). The Supergrid is built to prevent the Grid from being overloaded between the large generating stations and the main consumer areas.

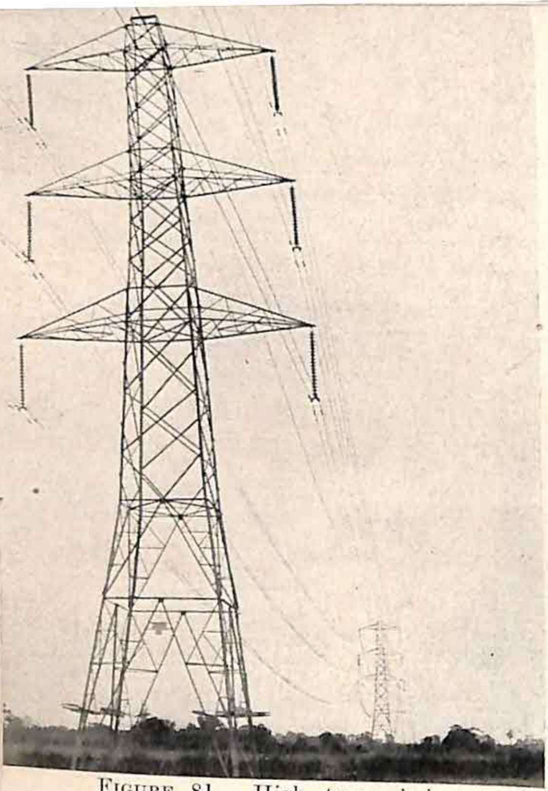
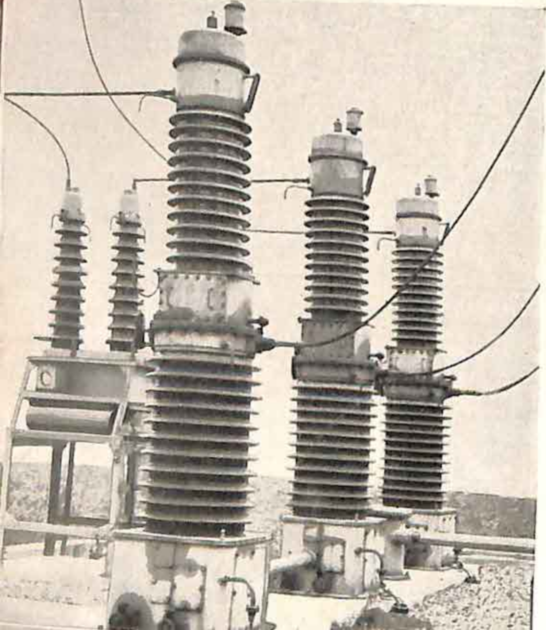


FIGURE 81. High transmission towers carry the lines of the 275,000 volts Supergrid across the country. They are 136 feet high and weigh nearly 11 tons.

FIGURE 82. An air-blast circuit-breaker for 132,000 volts.

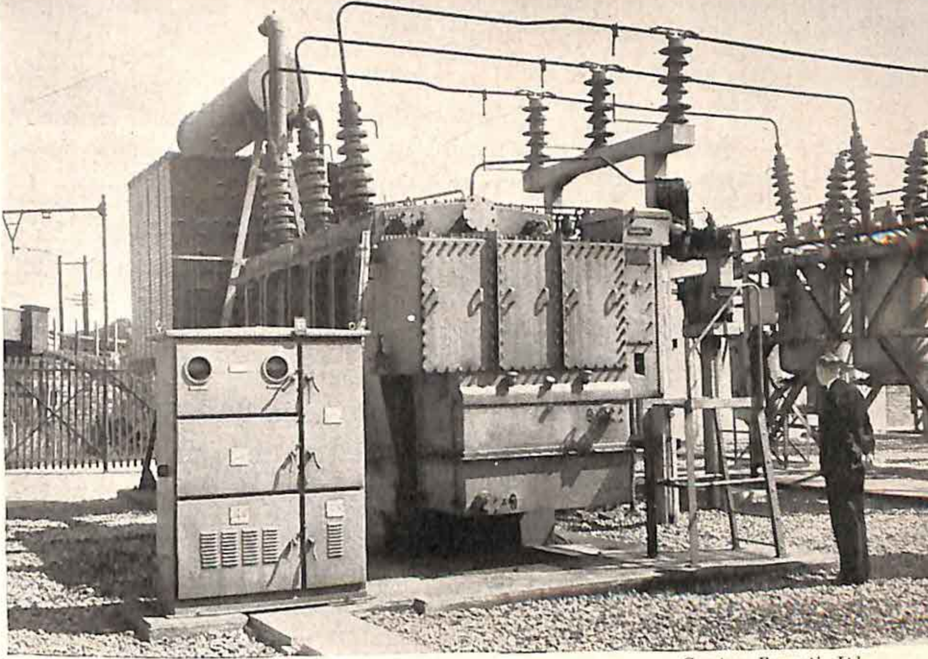
Courtesy Central Electricity Authority



The transmission lines themselves are generally made of aluminium and strengthened by a core of steel-wire. Why are they not made entirely of steel or entirely of aluminium? Why are silver and copper (which are good conductors) not used for transmission lines? The lines are suspended from long porcelain or glass insulators carried high above the ground on steel towers (pylons).

As the amount of power supplied by the generating stations is considerable, large currents flow through the overhead transmission lines and underground cables. Large *circuit-breakers* (or switchgear) are therefore employed.

In most high tension circuit-breakers the contacts are completely immersed in oil and the opening and closing is done by strong springs. These springs are operated by powerful solenoids controlled from a distance. The oil quenches the big



Courtesy Ferranti, Ltd.

FIGURE 83. A three-phase "step-down" transformer in a sub-station.

spark which is created when the circuit is opened. Some circuit-breakers are made which use a sudden and strong air-blast to kill the spark.

At various places on the 132,000 volts Grid system there are sub-stations which "step-down" the pressure from 132,000 volts to 66,000, 33,000, 11,000, and 6,600 volts, according to the requirements, for distribution

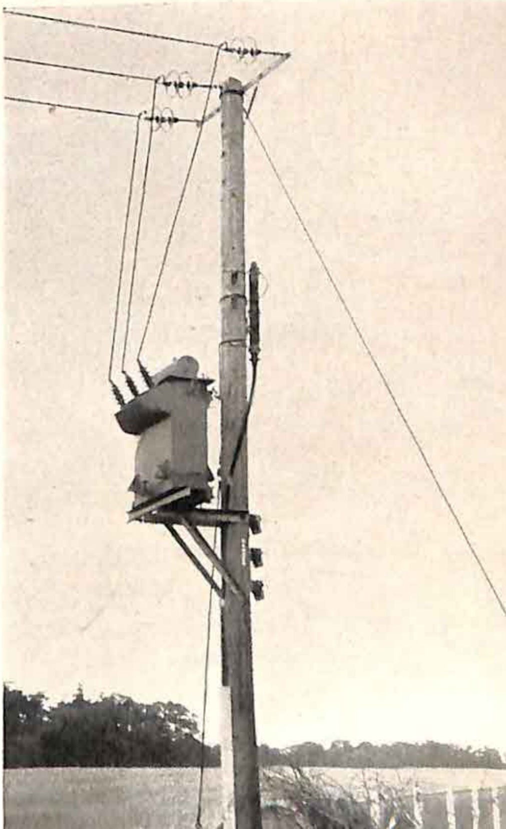


FIGURE 84. A sub-station mounted on a pole for the supply of a small community.

to the many smaller sub-stations situated in or near towns and villages. These smaller sub-stations "step-down" the pressure still further to 415 volts. All these sub-stations handle the three-phase system. Eventually one phase is supplied to an individual house by two wires only. You will see in Figure 78 that a fourth wire or neutral conductor is used. Note how three buildings in a row are connected to obtain a 240 volts single-phase supply from the 415 volts three-phase system, and how a small factory, such as a bakery or saw mill, uses all three phases for its electrical machinery. The electric railway shown is supplied from a convertor station changing the 11,000 volts A.C. to 660 volts D.C. A factory is shown with its own sub-station converting the 11,000 volts supply to 415 volts for driving heavy machinery and to 240 volts for lighting and heating.

NOTES ON THE UNIT

A *freely-suspended magnet* sets itself in a north and south direction.

Substances which are attracted by a magnet are *magnetic*.

Magnetic substances are iron, steel, nickel, cobalt, and some alloys.

A magnet has two *poles*, never only one.

Like poles repel; *unlike* poles attract each other.

The certain *test of magnetization* is repulsion.

A magnet can be made (1) by stroking with another magnet,
(2) by using an electric current in a solenoid,
(3) by induction from another magnet.

Magnetization can be destroyed (1) by heating,
(2) by beating.

Steel is more difficult to magnetize than *soft iron* but retains its magnetization better.

Soft iron forms an easy path for magnetic lines of force. It is used for (1) electro-magnets,
(2) screening objects from magnetic fields.

Keepers help permanent magnets to retain their magnetization.

Electricity flowing in a *clockwise* direction in a solenoid induces a South pole at the nearer end.

A *shunt* in parallel with a *galvanometer* converts it into an *ammeter* to measure *current.*

A *bobbin* in series with a *galvanometer* converts it into a *voltmeter* to measure pressure.

Induced E.M.F. depends on the *rate* at which the magnetic lines of force are cut by a conductor.

A.C. is generated in an alternator with slip rings.

D.C. is generated in a dynamo with a split-ring commutator.

Frequency of an A.C. is the number of *cycles* completed per *second.*

The *induced E.M.F.* in an induction coil at " break " is much greater than it is at " make."

A *transformer* consists of a primary coil and a secondary coil mounted on a closed iron core.

A " *perfect* " *transformer* which has no loss of heat when it is working gives :

$$\frac{\text{Pressure supplied to primary coil}}{\text{Pressure induced in secondary coil}} = \frac{\text{Number of turns in primary coil}}{\text{Number of turns in secondary coil}}$$

$$\text{Power input to primary coil} = \text{Power output from secondary coil}$$

$$\text{Pressure} \times \text{Current in primary coil} = \text{Pressure} \times \text{Current in secondary coil.}$$

THREE USEFUL EQUATIONS :

$$\textbf{Current}\ (\textit{amperes}) = \frac{\textbf{Pressure}\ (\textit{volts})}{\textbf{Resistance}\ (\textit{ohms})}$$

$$\textbf{Power}\ (\textit{watts}) = \textbf{Current}\ (\textit{amperes}) \times \textbf{Pressure}\ (\textit{volts})$$

$$\textbf{Energy}\ (\textit{Units}) = \textbf{Power}\ (\textit{kilowatts}) \times \textbf{Time}\ (\textit{hours})$$

REVIEW QUESTIONS

1. How would you find out whether a piece of metal is magnetic or non-magnetic ? If it is magnetic, how would you find out whether it is magnetized or not ?

2. If you are given a magnet on which the poles are not marked, explain how to discover which the north pole is.

3. What means would you use to determine which of two similar bar magnets is the more strongly magnetized ?

4. You are given a long steel rod. How would you proceed to magnetize it so that it has north poles at both ends? Where would the south pole lie ?

5. Why do iron filings sprinkled on a sheet of paper trace out definite lines when the sheet is tapped gently ?

6. Sketch how you would wind insulated electric wire around (*a*) a long iron nail, (*b*) a U shape piece of iron, to form electromagnets. Mark the direction of the electric current and the positions of the magnetic poles produced in the iron.

7. How would you determine the direction of flow of an electric current in a wire, without cutting the wire of the circuit ?

8. A long bar magnet hangs vertically. By its side a long thin strip of metal foil hangs loosely. An electric current is passed through the foil. Draw a sketch to show the movement of the foil and explain why this happens.

9. How can you convert a galvanometer into (*a*) an ammeter, (*b*) a voltmeter ? Draw clear diagrams to illustrate.

10. Why is an ammeter connected in series in a circuit ? Why is a voltmeter placed in parallel with part of a circuit ?

11. Why do two iron nails suspended side by side in a solenoid fly apart when an electric current is passed through the solenoid ?

12. Why does the iron armature of a dynamo tend to get hot after it has been working for some time ? What is done to cool it ?

13. Explain all the transformations of energy that take place when electricity is made from coal. Make a sketch of the operations in an electric generating station.

14. Describe and sketch the way that electricity is transmitted from a generator in a power station to one electric lamp in a house. In your sketch show clearly the various circuits.

SCIENCE ON THE MARCH

The Air and You
Water and Life
The Weather and the Earth
Life and Food
Health
Energy and Engines
Hearing and Seeing
Electric Currents
Magnets and Electric Power
Earth and Universe
Heating and Cooling
Birth and Growth

LONGMANS